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STUDY OF SOLID ROCKET MOTOR FOR A SPACE SHUTTLE BOOSTER

FINAL REPORT

Report 1917-FR1 CR-123687 15 March 1972

aerojet solid propulsion company

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Report 1917-FR1

STUDY OF SOLID ROCKET MOTOR FOR A SPACE SHUTTLE BOOSTER

FINAL REPORT

Contract NAS8-28428

Data Procurement Document 314
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15 March 1972

Prepared For

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APPENDIXES

I. EXECUTIVE SUMMARY

This report documents the results of Aerojet Solid Propulsion Company's study of solid rocket motors for a space shuttle booster. This two month study was conducted under Contract NAS8-28428 and was directed toward definition of a parallel-burn shuttle booster using two 156-in.-dia solid rocket motors (SRMs). The study effort was organized into the following major task areas:

- System Studies
- Preliminary Design
- Program Planning
- Program Costing

A. SYSTEM STUDIES

The system studies covered the important aspects of the production, operation, and support of an SRM booster system. Key system study areas included:

- Reliability/Safety
- Abort
- Environmental Impact
- Recovery and Reuse

The basic question in the area of reliability and safety is "How will we manrate the SRM?" Aerojet's recommended approach to SRM manrating has three phases:

- Design for Reliability
- Test to Confirm Design
- Assure Product Quality

I.A. System Studies (cont)

The key to design for reliability is the application of requirement vs capability analysis. This probabilistic design technique provides a quantitative approach to designing the required reliability into each SRM component. This means that each design element or failure mode will have ample margin to withstand variability in operational requirements and material capabilities. In this way, greater assurance of system reliability is obtained than could be achieved through testing alone.

The shuttle vehicle study contractors indicate that SRM thrust neutralization is necessary to allow implementation of their vehicle abort plans. Forward end venting is recommended as the method of thrust neutralization. Two vent ports will be opened in the forward dome of each SRM on command. The ports will be formed by shaped charge cutting of the case membrane. The ports are sized to provide neutral or slightly negative net SRM thrust at any time during booster burn. Analysis of the port cover trajectories indicates that the ports will not endanger the orbiter in any abort situation.

From an environmental standpoint the main question relating to use of SRM boosters is the effect of the hydrogen chloride (HCl) in the rocket exhaust products. Evaluation of large solid rocket launch and static test experience indicates that there will be no short-term local problems from HCl.

In evaluating potential long-term effects, it is significant that SRM exhaust products from a 440 flight shuttle program will contribute less than 1 percent of the nation's HCl emissions. Despite millions of pounds of HCl emissions each year, HCl is not a global air pollution problem. Once diluted and dispersed, HCl does not represent a persistent or toxic compound. On this basis, it does not appear that the modest contribution to the atmospheric emissions of HCl resulting from SRM booster operations represents a significant environmental impact.

I.A. System Studies (cont)

Evaluation of booster recovery and reuse indicates that the basic shuttle program of 440 flights can be accomplished with 15 production SRM boosters. Each booster can be recycled in 90 days, allowing 21 days for vehicle integration and launch operations. Damage-free booster recovery appears feasible using parachutes and retro-rockets. SRM component refurbishment and reuse is routine. Analysis indicates that SRM case components have ample life expectancy to allow 30 reuses for each unit. Total booster program costs can be reduced up to 30 percent with recovery and reuse.

B. PRELIMINARY DESIGN

A baseline SRM configuration was selected for the preliminary design phase. This baseline 156-in.-dia SRM, shown in Figure I-1, contains 1,000,000 lb of propellant and is designed for use in pairs to form a complete booster stage for a parallel-burn rocket assisted orbiter configuration. The booster stage structural components are designed to attach the SRMs to the orbiter HO tank. Booster thrust is transmitted to the HO tank through the forward attach structure. The SRM thrust and operating pressure vs time performance is indicated in Figure I-1. A summary weight statement also is shown.

The fixed ablative-lined nozzle is canted at 15 degrees to locate the thrust vector through the vehicle center of gravity. The segmented D6aC steel motor case has two center segments joined to each other and to the forward and aft closures by pin and clevis joints. A maximum expected operating pressure (MEOP) of 1000 psia was selected for design purposes as being representative, but not necessarily optimum.

The propellant grain is a circular-port configuration with a star shape in the forward closure. The forward face of the aft closure grain is restricted, but the other grain ends are allowed to burn, providing a regressive thrust-time characteristic. The propellant is an 88% solids HTPB

I.B. Preliminary Design (cont)

formulation. Insulation for the case is a conventional butadiene acrylonitrile rubber system with silica and asbestos fillers. The fore-end ignition system is a solid propellant gas operator initiated by redundant EBW systems.

Stage components include forward and aft attach structures, a base support structure, a nose fairing, a destruct system, and a complete instrumentation package.

Thrust neutralization and thrust vector control (TVC) systems were treated as design options for the SRM. The flexible seal movable nozzle TVC system is designed for $\pm$ 5 degree thrust vector deflection capability. Nozzle movement is controlled through two hydraulic servoactuators. Power is supplied by two redundant, battery powered hydraulic pumps.

In addition to the baseline design definition, parametric design data were generated for a range of SRM propellant weights and burning durations.

C. PROGRAM PLANNING

Both the DDT&E program and the production program for the SRM boosters will be accomplished at the Aerojet Dade County, Florida large rocket facility. The schedule for the DDT&E phase is shown in Figure I-2.

The baseline SRM (no TVC) development program can be completed within 36 months from Authority-to-Proceeed (ATP). Addition of a TVC system will add 6 months to the total program span. Delivery of the first set of insulated segment sections is the principle driver on the schedule; 16 to 18 months is quoted as the most probable fabrication period. On this basis, the first development test will be conducted in the twenty-first program month.

I.C. Program Planning (cont)

The ATP date was selected to permit completion of all motor firings (with TVC) prior to start of flight-test motor processing. The allotted 3-month span between ground tests could possibly be reduced for the last two manrating motors when the first production cast/cure facility comes on-stream. However, the added complexity of these tests suggests a conservative approach be taken, and accordingly, no schedule adjustment has been made. All motor and stage components and subsystems will have completed bench-testing qualification prior to incorporation on a manrating test motor.

The schedule is realistic and even slightly conservative. If a more accelerated effort is necessary the following steps may be taken:

Order segment billets prior to the program ATP (during the Design Definition phase)

Provide for a motor processing facility independent of the test site (the available facility is planned for both functions)

The full-scale SRMs to be statically test fired in the manrating phase of the DDT&E program will be as nearly identical as possible to a flight operational stage. Each test will be conducted in a manner simulating actual mission profiles. TVC duty-cycles (if applicable) and ordnance activation will be programed to duplicate typical flight sequences. Except for some stage structural elements such as the base support skirt, all new hardware will be used on each manrating SRM.

The SRM booster production schedule is shown in Figure I-3. Most major SRM components will be shipped from suppliers to Aerojet's Dade facility for processing and assembly. However, certain stage components such as the nose fairings and aft support skirts will be delivered directly to KSC.

I.C. Program Planning (cont)

The internally insulated case segments will be received via railroad car at the Dade facility. Shipping covers will be removed and the insulation abraded by grit blasting. A liner material will be applied to the prepared insulation surface and cured to provide a reliable propellant bonding surface. The segments will be assembled for propellant casting by inverting to the vertical attitude and positioned on a casting base. The inert operations will span an eleven-day period.

A casting core will be installed into the lined segment and the assembly positioned on its transporter under the casting stand. Mixing bowls of propellant will be positioned on the casting stand above the segment. Propellant is cast at ambient pressure through a bayonet maintained at or just below the propellant surface. Cure of the propellant is accomplished in ten days at 110°F. Upon completion of cure, the casting core will be extracted and cleaned for reuse. The segment will then be transported to the nondestructive test facility.

In the final assembly building, the igniter will be installed in the forward segment and the nozzle on the aft segment. Other subsystem hardware will be installed, final inspections and checkouts of the segments and subsystems performed, and final painting of the segment accomplished. Transportation covers will be installed and the motor segment set transported to the shipping and storage building. The entire motor processing sequence will be accomplished in 36 days.

Shipment of SRM segments to the KSC launch site will be accomplished by barge. Segments will be inverted in the shipping building and placed forward end up on a shipping pallet on the barge deck. Environmental covers and monitoring equipment will be installed. Two complete SRM sets will be shipped on each barge trip.

I.C. Program Planning (cont)

Final assembly of SRM segments, installation of stage subsystems, and systems verification testing will be conducted in the VAB. The projected time required to assemble, check-out, and prepare two SRMs for mating with the HO tanks is 134 hr.

SRM booster quality assurance plan will incorporate product verification methods consistent with manrating, design, and cost effectiveness requirements of the shuttle program.

The methods that will be used are primarily:

Raw material and process controls at each Aerojet supplier

Fabrication control and product inspection at designated assembly levels

Integrated assembly verification of motor segments and completed assemblies

Acceptance testing of operable components and subsystems

Each selected supplier of major components will be served by a resident Aerojet quality engineer to ensure continued maintenance of inspection procedures and documentation. When components and major assemblies are completed, Aerojet will conduct independent verification of critical characteristics and dimensional configurations. Gaging and laser inferometers will be used extensively to ensure a fabrication-to-flight integration of booster segments and systems to the shuttle.

To detect any errors in process or materials control, a comprehensive program of propellant verification will be imposed. Complete laboratory analysis will be conducted on each batch of propellant from submix to final formulation. Cure rates and final propellant physical and mechanical properties are also 100% verified to be within allowable limits. Each cured segment is final inspected by radiographic and ultrasonic methods. A complete leak

I.C. Program Planning (cont)

check and systems verification testing after motor assembly completes the inspection requirements.

The quality attained during the entire production cycle will be verifiable by NASA through a comprehensive documentation program that provides checks of all critical parameters and processes.

D. PROGRAM COSTS

The extensive technology base existing for large solid rocket motors allowed a costing approach for this study that is similar to that used in a proposal for procurement purposes. Subcontractor and supplier estimates were obtained on a bid basis for all major materials and components. Actual experience was used in the preparation of Aerojet estimates for engineering, manufacturing, quality control, and support functions.

The costs for this study are based on the following ground rules:

- All costs are in 1970 dollars with no escalation
- Contractor fee is not included
- KSC facilities are not included
- Basic operational mission model consists of 440 flights
- Parallel-burn 156-in.-dia SRM booster with 1,000,000 lb of propellant

Costs for the basic 156-in.-dia SRM booster without TVC and thrust neutralization are shown below:

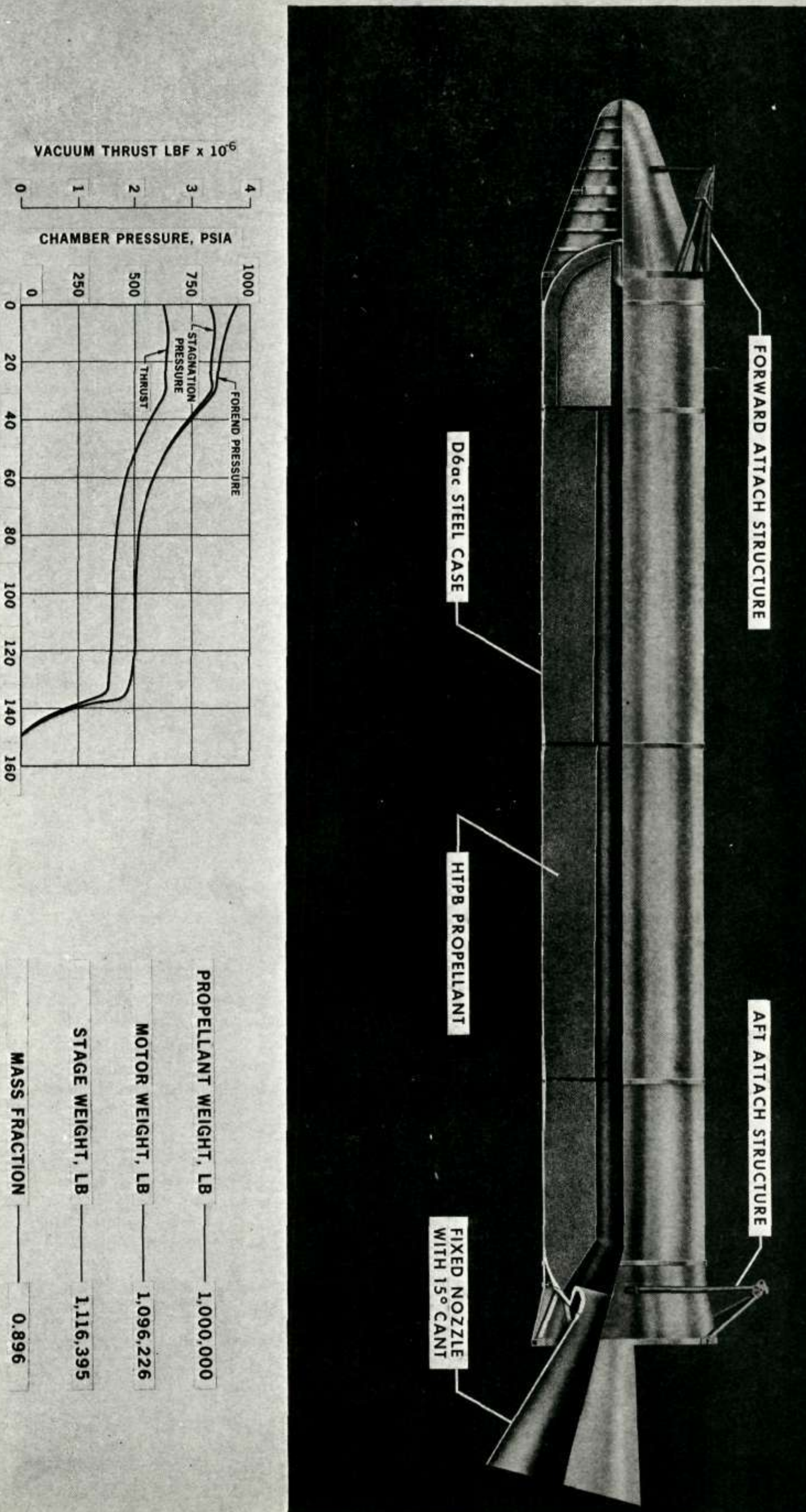
I.D. Program Costs (cont)

($ in millions)	Nonrecurring DDT&E	Nonrecurring Facilities	Recurring	Total
Baseline Program				
SRM	76.4	112.4	1,307.5	1,496.3
Stage	21.1	-	343.1	364.2
Total (Baseline)	97.5	112.4	1,650.6	1,860.5

Thrust Vector Control and Thrust Neutralization (TN) have been costed separately and are presented in additive options:

($ in millions)	Nonrecurring DDT&E	Nonrecurring Facilities	Recurring	Total
Options				
TVC	11.4	-	140.6	152.0
TN	2.3	-	46.9	49.2
Total (Options)	13.7	-	187.5	201.2
Total Program with Options	111.2	112.4	1,838.1	2,061.7

Additional costs are provided in Section III of this report for different launch rates and for other SRM propellant weights. The cost effects of SRM recovery also are presented.



Baseline 156-In.-Dia SRM Stage

Figure I-1

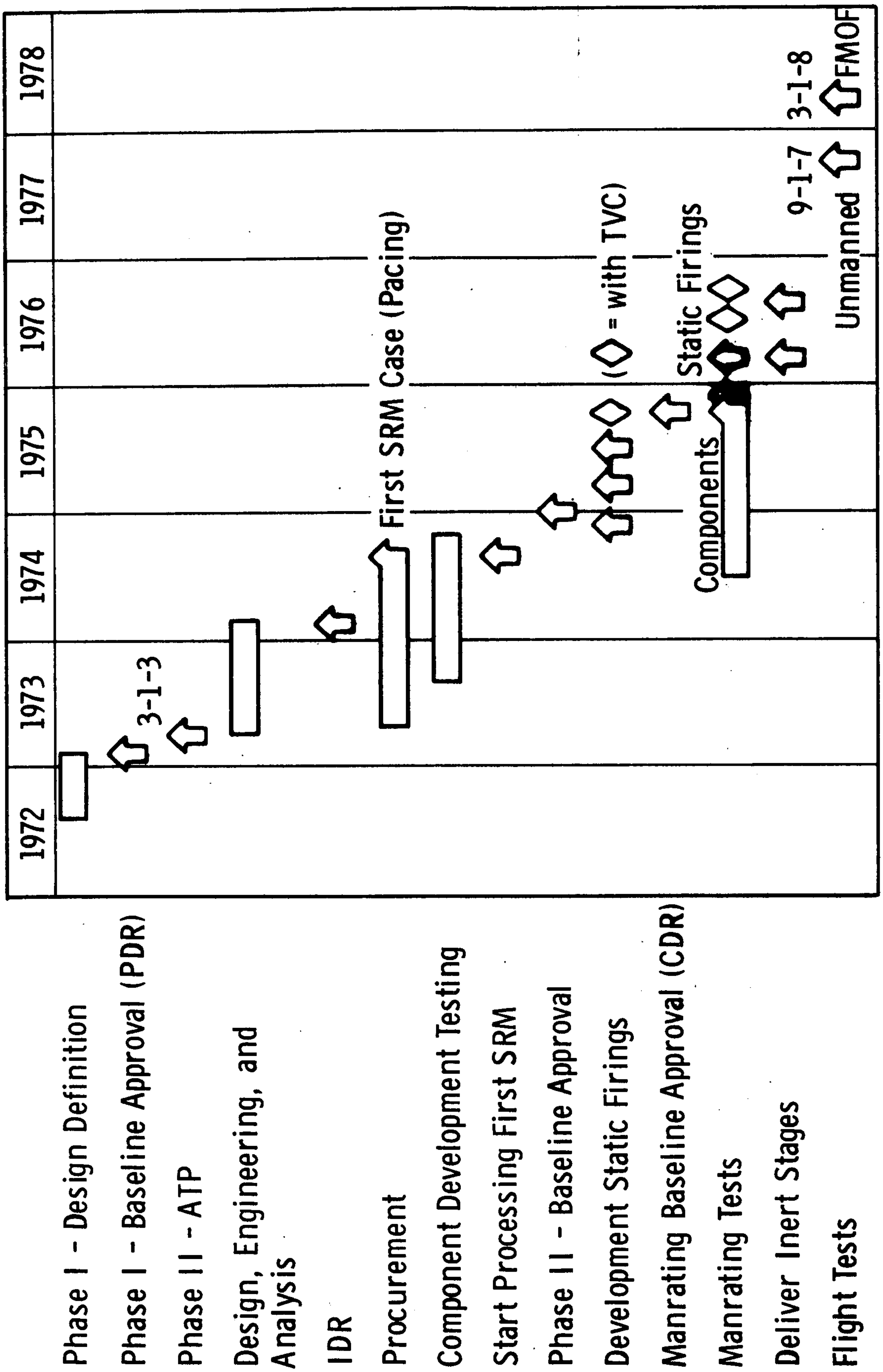
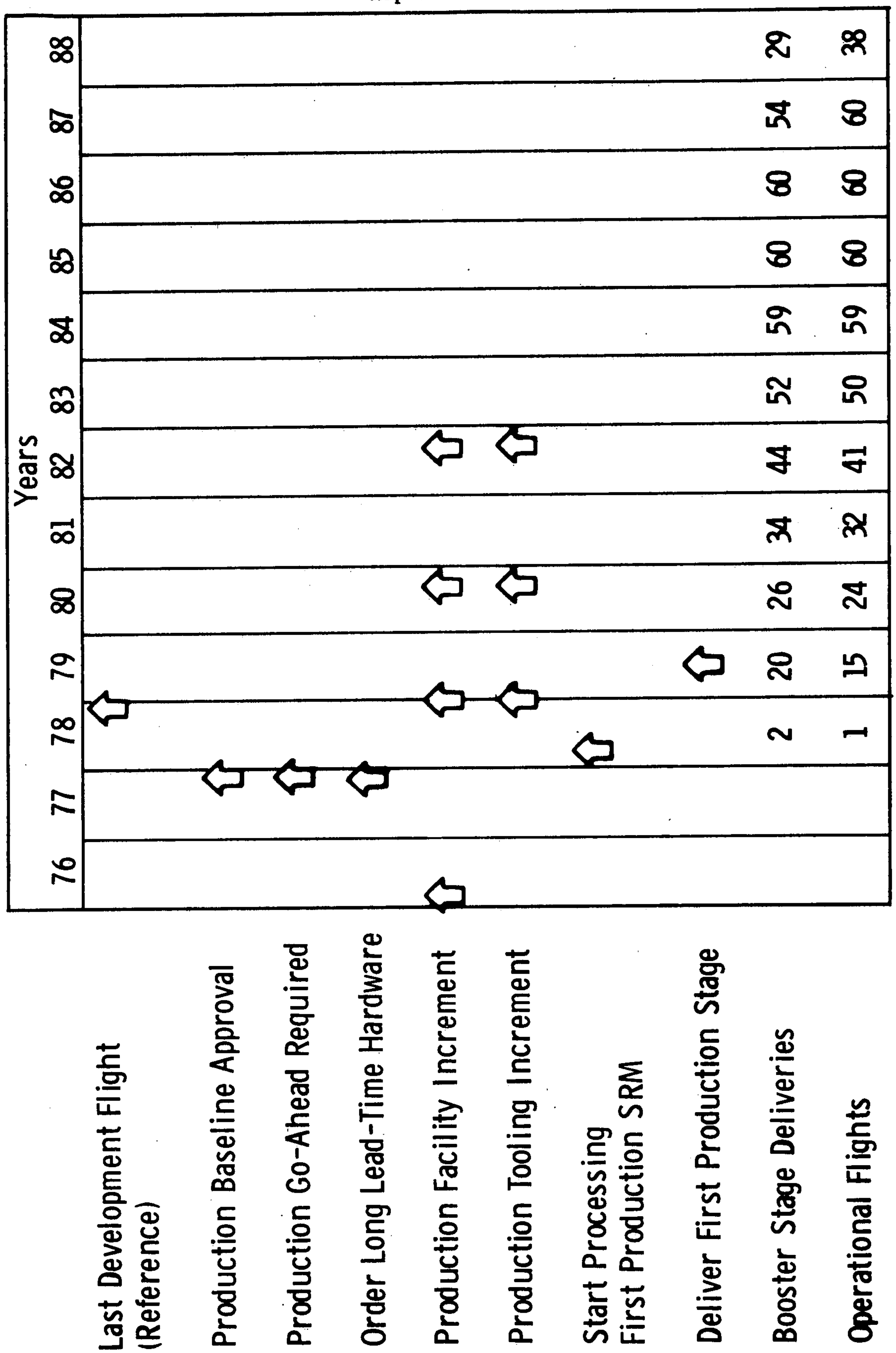


Figure I-2

DDT&E Schedule



Production Program Schedule

Figure I-3

II. TECHNICAL DISCUSSION

A. INTRODUCTION

The technical effort on this program consisted of system studies and preliminary design work for a parallel-burn shuttle booster using 156-in.-dia solid rocket motors (SRM's). The system studies were directed toward the following key areas:

1. Reliability/Safety
2. Abort
3. Acoustic and Thermal Analysis
4. Environmental Impact
5. Recovery and Reuse

Each of these areas is discussed in the following section of this report. Additional system studies were performed to investigate booster manufacturing, transportation, and launch operations. The results of these studies are included in the discussion of booster program plans and costs in Section III of this report.

A baseline SRM configuration was selected for the preliminary design phase. This baseline 156-in.-dia SRM contains 1,000,000 lb of propellant and has a fixed canted nozzle. The booster stage structural components are designed for a shuttle vehicle with two parallel-burn SRM's attached to the orbiter H-O tanks. Thrust vector control and thrust neutralization were treated as design options for the SRM. Parametric design data were generated for a range of SRM propellant weights and burning durations.

II. Technical Discussion (cont)

B. SYSTEM STUDIES

1. Reliability/Safety

The basic question in the area of reliability and safety is "How will we manrate the SRM?" Aerojet's recommended approach to SRM manrating has three phases:

— Design for reliability
— Test to confirm design
— Assure product quality

The first step in designing for reliability will be to perform a failure modes, effects, and criticality (FMEC) analysis for the SRM booster system. This analysis will provide an understanding of the potential failure modes for each design element in terms of the effects on mission success and crew safety. The FMEC analysis also will indicate the areas where design or product assurance techniques can best be used to break the chain of events leading to failure.

Prior experience with FMEC analysis for solid rocket motors and stages leads us to specify that fail-safe or redundant designs be used in all dynamic systems on the SRM booster for the space shuttle. This means providing redundant firing units and initiators for all ordnance functions, redundant shaped charges for thrust neutralization port cutting, and dual hydraulic power systems for movable nozzle thrust vector control (TVC).

The SRM design will include a safety monitoring system to provide indication of abnormal SRM performance. One element of this system will be an ignition firing unit condition monitor that will preclude booster ignition unless all redundant units on each SRM are in ready condition. During booster burn the SRM operating pressures will be monitored to detect any deviation from normal performance. The TVC system also will be instrumented to detect any anomalous performance. If desired, these sensors can be tied into an automatic abort implementation system in the shuttle orbiter.

II.B. System Studies (cont)

The key to design for reliability is the application of requirement vs capability analysis. This probabilistic design technique provides a quantitive approach to designing the required reliability into each SRM component. This means that each design element or failure mode will have ample margin to withstand variability in operational requirements and material capabilities. In this way, greater assurance of system reliability is obtained than could be achieved through testing alone.

The requirement vs capability technique requires that the desired system reliability first be allocated to each design element or failure mode using traditional FMEC analysis and mathematical modeling techniques. Next, the requirement or nominal stress for each significant design element is determined using appropriate design formulas. Variability estimates are made from material data and tests for both the requirement and the capability. The determination of the probabilistic design margin needed to achieve the allocated design element reliability is then obtained from the relationship:

$$\text{Required margin} = K\sqrt{\sigma_R^2 + \sigma_C^2}$$

Where K = Failure probability factor
σ_R = Variability of requirement
σ_C = Variability of capability

The factor K varies according to the reliability requirement. For example, if the reliability requirement for a design element is 0.999999, the K factor is 4.75. The design nominal of the capability or strength distribution is then calculated from:

II.B. System Studies (cont)

$$\overline{X}_C = \overline{X}_R + K\sqrt{\sigma_R^2 + \sigma_C^2}$$

where $\overline{X}_C$ = nominal capability

$\overline{X}_R$ = nominal requirement.

The application of this technique to a typical design element is shown in Figure II-1.

Aerojet pioneered the application of this technique to solid rockets motors during the 260-in.-dia motor program, applying the analysis to elements in the insulation, case, propellant, and ignition systems. Further progress was made in the NERVA program where the stringent manrating and safety requirements led to improved computerized methods employing the Monte Carlo analysis and the finite element techniques with combined thermal and stress analyses. Because of the interrelations between many of the parameters affecting both requirement and capability distributions, partial differential and co-variance estimating techniques have been developed by Aerojet. These methods significantly increase the accuracy and applicability of this probabilistic design tool.

The second phase in manrating the SRM booster system is testing to confirm the design. The conventional approach of obtaining a statistical reliability demonstration through extensive full-scale testing is neither practical nor necessary for the SRM booster. Instead, a balanced program of material, component, subsystem, and full-scale tests will be used to validate the SRM design.

The planned test program will be used to confirm or modify the elements of the requirement vs capability analysis of the initial design. As the testing progresses the design reliability assessment will be continually updated. If necessary, design or operational adjustments will be made to assure that the SRM design reliability goal is achieved.

II.B. System Studies (cont)

Test objectives are clarified when viewed as an adjunct to reliability assessment through requirement vs capability analysis. Instead of testing simply to demonstrate adequate performance, each test is designed to yield a maximum of information on the real values of design element requirements and capabilities. This frequently will require more extensive test instrumentations than would be used in an ordinary acceptance test. The SRM test program described in Section III of this report makes use of this approach to maximize test efficiency.

The final phase of manrating consists of assuring the quality of the production SRM boosters. This will be accomplished using a rigorous quality assurance plan encompassing the best features of current practice. The planned flow of quality assurance activity is shown in Figure II-2.

Activity begins at supplier facilities with quality engineering surveillance, source acceptance, and acceptance testing. All incoming material and components pass through receiving inspection. During SRM processing and assembly, all operations are controlled through integrated manufacturing and inspection planning. Extensive checks and verifications are performed throughout the process. For example, dozens of tests are run on each batch of propellant cast into an SRM. Raw materials, intermediate mixtures, and final propellant batches are scrutinized so that the characteristics of every pound of propellant used in the SRM are known. After completion of processing, each SRM segment will be inspected with sensitive NDT techniques to assure that no fabrication errors were made. This comprehensive understanding of the as-built characteristics of the SRM will be used as the basis for a final reliability assessment for each production unit.

Historical reliability experience with solid rockets shows that high levels of reliability are achieved. As an example, the failure experience for Aerojet-produced Minuteman operational stages shown in Figure II-3.

indicates that only one critical failure has occurred in over 500 flight and static tests. These advanced propulsion systems were designed for high performance and required extensions in the state-of-the-art, Reliability goals were less stringent than would be anticipated for manned applications. In the category of manrated solid rockets, Aerojet has produced hundreds of thousands of JATO units for manned aircraft. These rockets are licensed by the Federal Aviation Agency for use on manned aircraft and have an observed reliability of 0.999996.

2. Abort

The shuttle vehicle about plans defined by the vehicle study contractors require that the SRM booster be capable of thrust neutralization or termination at any time during booster burn. Methods for achieving this are discussed below, together with an analysis of the operational aspects of the selected forward head venting method.

a. Water Quench With Pressure Venting

The simultaneous application of water to the propellant burning surfaces and a rapid venting of the chamber pressure has been used to extinguish solid propellant burning. This type of system could be considered for on-pad aborts where damage to launch facilities and possible ignition of the orbiter fuel and oxidizer is a concern. Water for the quench could be stored external to the booster. To provide this same capability in flight would place a heavy weight penalty on the booster. In addition to the water which must be carried, there would be a pressurization system, a large explosively-actuated valve, and an insulated injector assembly.

The overriding factor which eliminates a quench-type abort system from serious consideration is the uncertainty that it could, in fact, accomplish extinguishment of propellant burning. Success to date with such an approach has been limited to small motors having relatively simple grain

II.B. System Studies (cont)

configurations. The 156-in.-dia SRM design has features which tend to preclude successful quench; very long grain bore with a large free volume, complicated front-end grain geometry, and most important, burning between the segment grain faces where water penetration would all but be impossible to attain. The development of a system to fully extinguish a 156-in.-dia SRM would completely overshadow the rest of the SRM development program, with no assurance of success.

b. Aft Head Venting

Explosive removal of the nozzle and a section of the aft dome would result in a reduction of forward thrust to a level where the vehicle thrust-to-weight ratio is below 1. However, this method subjects the entire vehicle to a severe shock loading which could be structurally damaging. In addition, TVC actuators, hydraulic and electrical connectors would have to be severed. The system would be costly, complicated, and relatively ineffective. The only advantage is restriction of debris and exhaust to areas away from the orbiter and tankage.

c. Cylinder Venting

This method also would be effective in rapidly reducing pressure and thrust to levels where safe separation could be accomplished. The most feasible application would be in a series burn configuration. There is no location on the parallel-burn SRM where cylinder venting could be tolerated without subjecting the H-O tanks to unacceptable structural loads or the orbiter to direct exhaust and debris impingement.

d. Opening of ports on the forward head of SRM's to achieve neutral or reverse thrust is a well established and characterized technique. This method has been used on many missiles for impulse control. Aerojet has a wealth of experience on forward venting thrust termination system design and performance from the Minuteman and Polaris programs. The Titan IIIC 120-in.-dia SRM boosters also incorporate forward head venting.

II.B. System Studies (cont)

e. Selected Approach

Based on evaluation of the potential methods for thrust neutralization (TN) of a parallel-burn SRM booster, the forward head venting method was selected. The system functions through shaped charge cutting of two diametrically opposed ports in the forward dome of the SRM. The ports are sized and located to provide zero net thrust from the SRM under vacuum conditions. This system, which is described in detail in Section II.10 of this report, will accomplish neutralization of the forward thrust within a few milliseconds of command. Motor chamber pressure will decay to below 200 psi within 130 milliseconds. The command signal to initiate TN will be given simultaneously to both SRMs regardless of the reason for the abort decision. The system design enables venting at anytime during the boost phase.

A concern with forward end venting is the exposure of orbiter and H-O tankage to debris and exhaust products from the SRMs during the TN sequence. The possibility of impact between orbiter and the cutout heat sections is a potential problem area; thermal envelopment and particle (aluminum oxide) impingement or deposition is another. To better understand these phenomenon, studies were conducted to define exhaust port trajectories and the exhaust plume envelope at various times during the mission.

f. Investigation of Thrust Neutralization Exhaust Plume Characteristics

Booster thrust neutralization can occur at any time from ignition on the launch pad until booster burnout at 175,000 to 200,000 ft altitude. The characteristics of the reverse thrust propellant exhaust was examined at three conditions: launch at sea level, intermediate flight at 70,000 ft, and booster burnout at 175,000 ft.

The conventional thrust neutralization port concept used in this study requires two ports in each motor, each port having a throat area slightly larger than that of the motor primary nozzle. Each port consists of

II.B. System Studies (cont)

the throat and a conical exhaust stack of relatively small expansion ratio. The stack centerline is inclined 35 degrees to the SRM centerline and the exit is cut off at an angle governed by the motor fairing surface angle at the stack exit location. Actuation of the ports reduces the SRM chamber pressure very rapidly to less than 200 psia.

The condition at sea-level abort is depicted in Figure II-4. The forward vent exhaust expands to a maximum diameter ratio of approximately two and forms the cyclic pattern illustrated. Although the plumes are inclined from the TN port centerlines because of the skewed stacks, no direct impingement on the orbiter or H-O tank is anticipated. Solid particles (primarily aluminum oxide) and gas in the propellant exhaust are well mixed.

The plume characteristics change with vehicle altitude and velocity. With the attainment of supersonic vehicle speeds, the port exhaust at abort conditions will act like quasi-solid bodies in the air stream, creating bow-shock structures located some distance forward of the stack exits. Figure II-5 shows schematics of such structures. At 70,000 ft altitude and an assumed vehicle velocity of 2,200 ft/sec, the interaction shock is located near the SRM bow wave location and would merge with it (the stack exhaust plumes replace the SRM body as the prime local disturbance). There is a double shock structure, with an interface between air and exhaust located between the shocks. Although oxide particles in the exhaust do not fill the entire gas plume, they will not penetrate the air-side shock surface; rather, they will turn and move outward between the shock surfaces in a relatively dense zone. This zone of gas and particles will impinge on the orbiter and its tankage.

Abort near the end of the booster-powered flight will produce the plume characteristics pictorially shown in Figure II-6. The exhaust will force the interaction shock structure completely away from the vehicle system. Essentially, there will be two plumes, one of gas as shown and one of particles, the bulk of which are restricted to an expansion cone of 90 degrees or less. It is not clear at this time whether the particles

II.B. System Studies (cont)

will impinge on the orbiter to an extent that a thermal evaluation should be made. However, some particle "snow" should generally cover the vehicle surface.

The significance of exhaust impingement on the shuttle vehicle has not been studied in this preliminary analysis. However, some interaction of TN exhaust particles and gases with orbiter and the H-O tank is indicated at all conditions other than low altitude and low flight velocity. Further evaluation of these effects is needed.

g. Investigation of Thrust Neutralization Port Cover Trajectory

Two vehicle conditions were considered as probable worst case situations. These were the maximum dynamic pressure condition at the end of the boost phase. Only the pressure vessel thrust neutralization (TN) port chamber cutout disks were considered during the analysis. Other smaller items, such as the stack covers, were not considered significant. Each port disk was assumed to be a flat, two dimensional plate with a diameter of 49.5-in. and weighing 284 lb.

It was postulated that each disk would travel through three separate flow fields after initiation of thrust neutralization. The first would be that traversed by the disk in the vehicle TN exhaust stack. Here it would be given its initial acceleration by a pressure force after being explosively released. In the analysis, it was assumed that this pressure force was constant along the length of the stack and that the magnitude of the driving pressure corresponded to the total pressure, modified for a sudden expansion of the motor chamber gas. At the exit of the stack the disk enters the second flow field, the TN port expanding exhaust plume. Here the disk is accelerated away from the vehicle by the high velocity exhaust gases. On reaching the plume boundary the disk enters the third flow field, that corresponding to the free air stream. In this flow field the disk encounters a retarding drag force and undergoes trajectory directional change.

II.B. System Studies (cont)

Use was made of a particle trajectory computer model to establish trajectories for the disk. Two different drag coefficients, 1.75 and 1.0, corresponding to a plate at 90 degree angle of attack and to a sphere were used to investigate effects of spinning or tumbling of the disk on drag forces. Comparatively little difference in trajectories was noted for the two coefficient magnitudes; hence, disk spinning effects on drag forces were not considered to affect the basic results of this study.

Results from the preceding analysis defining plume behavior for the TN port exhaust were used to establish the plume-air stream interface distances and plume flow fields. For the maximum dynamic pressure condition, the plume is of a finite size and there exists in the vicinty of the vehicle an interaction shock disturbance. This disturbance is a double shock structure, with an interface between air and exhaust located between the shocks. Essentially, plume gases will not penetrate the air-side shock surface; rather they will turn and move outward between the shock surfaces. Conversely, air will not penetrate the exhaust-side shock surface but will flow around the shock surface. Schematics of the shock structures for the maximum dynamic pressure condition are shown in Figure II-5.

At the end of boost conditions the TN port exhaust plume interaction shock will be located far away from the vehicle. Thus for the purposes of this study the disk would not be affected by an air stream flow field but instead would remain completely immersed in TN port exhaust gases while passing out of range of the shuttle vehicle.

For the initial acceleration phase it was calculated that the disk would be traveling at a velocity of 520 ft/sec upon leaving the TN port stack exit (approximately 6 ft of travel distance) at an average acceleration of 22,500 ft/sec^2. The driving pressure in the stack was calculated to be 420 psia (80 percent of the steady-state chamber pressure) and was assumed constant along the entire 6 ft length.

II.B. System Studies (cont)

Next, the trajectory of the disk through the exhaust plume flow field was calculated. The plume was considered to be skewed approximately 15 degrees with respect to the stack centerline because of assymmetry due to the cut-off stack exit plane. It was assumed that the initial direction of the disk was displaced 30% as much as the gas from the stack centerline. For the maximum dynamic pressure case, the trajectory calculations for the disk in the plume indicate that the disk accelerates to 717 ft/sec velocity by the time it reaches the air exhaust interface, 21 ft from the port stack exit. The disk does not deviate from its original direction during its traverse of the plume, following a basic assumption of spherical source flow in the original definition of the theoretical plume.

After passing through the interface and into the air stream at the condition of maximum dynamic pressure, the disk begins to decelerate losing approximately 3.6 ft/sec of velocity per ft traveled for the first 100 ft. Approximately 167 ft of travel would be required to stop the disk relative to the shuttle vehicle. It is noted that this distance does not include the effect of velocity degradation of the vehicle once TN is initiated. Accounting for this effect would increase the relative distance.

The calculated trajectory of the disk for the maximum dynamic pressure condition in the free stream indicates that the disk will deviate from its original direction of travel at a relatively small rate that increases exponentially with distance traveled. Thus, appreciable deviation velocities will not be achieved until the disk leaves the vicinity of the vehicle. At a distance of 125 ft the deviation velocity is 118 ft/sec; at 146 ft deviation velocity equals axial velocity (160 ft/sec). Figure II-7 presents a plot of the disk trajectory relative to the vehicle.

Near the end of the boost phase the disk will not escape the plume exhaust field while it remains in the vicinity of the vehicle. It will continue to accelerate away from the vehicle in a straight line.

II.B. System Studies (cont)

The results of this analysis indicate that the TN port disk will continue essentially in the initial direction it has when it leaves the exhaust stack. Under normal circumstances for the two flight conditions considered, this direction does not impinge upon any vehicle structure, thus no danger of impact exists. Furthermore, the trajectory of the disk, once it leaves the immediate vicinity of the vehicle is such that the possibility of a delayed impact between vehicle and disk is extremely remote. Because of the high accelerations associated with the disk, the effects of gravity are relatively small. Similarly, vehicle angle-of-attack variations have small influence on the problem. These conclusions apply to any part of the boost trajectory.

The disk could impact the vehicle if an abnormal situation such as physical deflection or explosive charge malfunction causes it to leave the exhaust stack in a radically skewed direction. It is estimated that more than 45 degrees error from the nominal trajectory could be tolerated without incurring an impact with the orbiter. It might be presumed that the trajectory error could not exceed the half-angle of the exhaust stack, but an analysis of TN malfunction modes has not been undertaken, and any conclusions on the consequences of TN system malfunction are premature at this time.

3. Acoustic and Thermal Analysis

a. Acoustic Analysis

A preliminary estimate has been made of the maximum sound pressure level expected at the aft end of the orbiter due to the acoustic field of the two baseline 156-in.-dia solid rocket motors. The overall sound pressure level is expected to be of the order of 165 db (ref. 0.0002 dynes/cm^2). The estimate is based on a free field condition assuming no deflectors of the exhaust stream nor any ground reflection. In addition, measured data from full-scale firings of the 260-in.-dia solid rocket motor and the observed acoustical efficiencies from these firings were used.

II.B. System Studies (cont)

It is anticipated that a liquid rocket booster would produce an acoustical environment similar to or more severe from a structural standpoint than the 156-in.-dia solid motors. The clustering of a multiple nozzle liquid engine will result in a reduction in the acoustic energy due to the multiple jets. However, the apparent source of the lower frequency noise also will be much closer to the exit plane of the engines than for a single layer solid motor. Based on observed data from the 260-in.-dia motor firings, the acoustical efficiency of the very large solid rocket motor is significantly lower than for small motors. The radiated total acoustic power of the jets was in the order of 6 to 8 db lower than would be expected based upon the total mechanical power of the jet.

It is anticipated that the acoustic environment produced by the solid rocket motor will be less severe than the equivalent multiple engine liquid system because the acoustic efficiencies of the large solid motors is lower and the apparent source of the significant acoustic energy is located further away from the vehicle.

b. Thermal Effects of Booster Exhaust Plume

The exhaust plumes of the solid rocket motor boosters will directly affect the shuttle vehicle structural design through the mechanism of convection and radiation heat transfer. Both of these modes occur together to cause heating of vehicle components in the base region; additionally, the interaction of each plume and the free air stream can result in flow separation along external forward surfaces and in this way can serve to transport hot gases well upstream of the vehicle base by means of convection in the separation region. The following paragraphs present general descriptions of the nature of the plume-generated heat transfer and discuss areas associated with the parallel-burn SRM shuttle configuration that deserve special attention and evaluation.

II.B. System Studies (cont)

(1) Base Heating Considerations

Radiant heating occurs at those vehicle surfaces in the missile base region that are directly exposed to the plumes. This type of heating is common to all rocket vehicle systems; however, there are some concepts associated with the radiation heating environment of the shuttle that are of particular interest. As an example, the radiation source is going to be affected by secondary combustion occurring between the fuel-rich H_2-O_2 exhaust of the orbiter's engines and the oxidizer-rich exhaust of the SRM boosters. The net effect will be to raise the temperature of local zones of the radiating source and hence increase overall heat-transfer rate. Generally, the thermal protection problems arising because of plume-generated convective heat transfer are an order of magnitude more severe than those due to radiation heat transfer. Thus, radiation thermal protection requirements normally are satisfied by those established for adequate convection heating protection.

Base heating by convection can occur as a result of the recirculation of gases in the normally separated base flow regions of a rocket motor. This recirculation occurs because of the entrainment of gases at the exhaust plume boundary and the necessity for replacement of the entrained gases by the entry of free-stream or propellant exhaust gases into the base region. The re-entry of exhaust gases is accentuated by the growth of the plume body at high altitudes; it becomes severe as large pressure gradients are created by the deflection of the free stream air around the plume. The severity of the base heating condition is further enhanced in the multiple nozzle configuration represented by the two booster nozzles and the main vehicle exhaust system. As the exhaust plume dimensions grow with altitude, there occurs a zone of interaction where the gas flows come together. The shock structure formed in the resultant deflection of the exhaust gases defines a region of locally high pressure that drives a considerable portion of the hot gases forward toward the missile base. In the extreme, this reverse flow chokes,

II.B. System Studies (cont)

achieving a high velocity as it enters the vehicle base zone. This is a direct, forced convection of hot gas that is normally relieved only by deflection or component remoteness.

The choking of plume interaction reverse flow is common to clustered nozzle configurations such as occur in Saturn or early Polaris and Minuteman motor designs. Its occurrence is alleviated in the twin booster configuration of Titan III, for example, because of the distances between booster centerlines and because the boosters were two in number. Even so, the plume interactions produced a high pressure zone potentially responsible for a localized zone of high convective heat-transfer rate at the missile base. A quantitative estimate of the driving pressure magnitude can be made readily as shown in Figure II-8 by establishing the angle at which discrete streamlines from each nozzle of a system will intersect so as to support the required pressure rise along the centerplane of interaction. All flow outside these streamlines will tend to be reversed and driven forward toward the base by the established pressure. Such an approach to analysis has been used historically for preliminary estimate purposes. Yet, it is generally accepted that although theoretical analyses of varying degrees of sophistication may be used in preliminary design, experimental evaluation and development is a current requisite to final specification for configuration layout and thermal protection.

(2) Heating of Forward Components

The same effects of interaction of free stream and exhaust plume and of interaction among exhaust plumes can be responsible for additional problems of convective heating forward of the booster and vehicle base regions. These effects occur because of the necessity for the supersonic air stream to flow around the plume boundary. At sea level, where the free-stream pressures may be of the same order of magnitude as the exhaust nozzle exit pressures, the expansion of the plume is minimal and the air stream is deflected little by the exhaust gas body. However, as altitude is achieved

II.B. System Studies (cont)

and the free-stream pressure is reduced by a few orders of magnitude, the plume body becomes large with respect to the local vehicle body dimension and a flow field similar to that shown in Figure II-9 is generated. Essentially, the free stream flow is deflected around the plume body. This results in pressure differentials that in the extreme cannot be supported in attached flow along the vehicle longitudinal body and the flow separates from the body to the extent that the shear layers conform to flow deflections that can be supported. There is a coupled effect in that the pressure rise in the free stream causes a reduction in the plume body size relative to its configuration as it would exist in still air. Nevertheless, the extent of the body flow separation has been shown experimentally to be related very closely with the ratio of nozzle exhaust pressure (inside the nozzle exit) to local free stream pressure.

Experiments have found little hysteresis in the flow separation occurrence except as physical body shapes (support struts, surface discontinuities, etc.) have influenced the tendency for separation or reattachment. It is common that at pressures related to high altitudes, an entire vehicle body can be found immersed in a region of separated flow. As Figure II-9 shows, there are two zones of flow recirculation under the conditions of plume-induced separation. One is in or near the base region and represents the replenishment of flow required by plume entrainment. The second is related to entrainment along the separation boundary shear layer, with its resultant requirement for replenishment. It follows that even in the presence of a rotationally symmetrical single-body vehicle, there is a flow boundary in the secondary flow region where plume gases mix with recirculating air and are transported forward along the missile surface.

The transport of hot gases forward is accentuated in a multibody vehicle system, for there are paths between the bodies where the forward transport can exist. The tendency is enhanced by the previously mentioned "between-nozzle" interaction effect that provides for an initiating source of gas movement. There follows an anticipation that the composite shuttle vehicle has potential susceptability to unusual problems of heating in base regions and in areas forward where hot gases may be propagated by flow interaction forces.

4. Environmental Impact

The potential use of solid rocket propulsion for the space shuttle requires consideration of the environmental impact of solid rocket motor operation. From an environmental standpoint the primary area of concern is the output of hydrogen chloride (HCl) in the rocket exhaust gas. Also of concern is the output of carbon monoxide (CO) and aluminum oxide particles (Al_2O_3). The composition of the exhaust products from a typical large solid rocket motor is shown in Figure II-10. The effects of these emissions in static tests and launch operations are discussed below:

a. Static Testing

Motor static tests differ from launches in that all of the propellant used is consumed at ground level. However, the high temperature of the exhaust gases causes them to rise in a buoyant plume. The downwind concentrations of the exhaust gases are dependent on the height of this buoyant rise, and any elevation contributed by the persistence of the exhaust jet.

Solid rocket motor tests are performed at relatively remote sites, and access to the sites is controlled. Suitable precuations are taken to ensure the safety of the test crew, including remote operation and protective equipment.

In-plant test firing of 156-in.-dia motors at the Aerojet Dade County Facility will be conducted at the CCT site in Area 21 of the plant. With a nominal propellant weight of 1 million lb per motor, the prime constituents of the exhaust gas that will be monitored during each test to assure no

II.B. System Studies (cont)

adverse effects on the environment will be about 211,000 lb of HCl, 205,000 lb of CO, and 378,000 lb of Al_2O_3. It is estimated that exhaust gas concentrations within the plant site will be well below the recommended threshold limit values for these materials.

Air sampling conducted by helicopters during static test firings of large solid motors at Aerojet-Dade in 1964 and 1965 yielded maximum HCl concentrations of less than 1 ppm measured in the exhaust cloud.[(1)(2)*] The thermal updraft from the motor firings affords efficient vertical mixing and horizontal dispersion of the HCl, resulting in a negligible concentration beyond the plant boundary downwind from the test site.

The CO generated during each test firing is negligible when compared with the quantity of this material emitted annually from sources within the United States. An estimated 102 million tons of CO was emitted into the atmosphere in the United States in 1968: 63% of this total was attributable to transportation sources; 2% to stationary sources; 11% to industrial processes; 8% to solid waste disposal; 7% to forest fires; and 9% to man-made sources. Analysis of these emissions for many representative metropolitan areas shows a range in total CO emitted from 5.3 million tons/year for the New York-New Jersey area to 152,000 tons/year for Steubenville, Ohio. The 100 tons of CO emitted from each 156-in.-dia motor test firing would have a negligible effect on the normal total in the atmosphere in Dade County, Florida.

II.B. System Studies (cont)

Al_2O_3 from the rocket exhaust will be additive to the normal particulate fall-out within the plant site and beyond the plant perimeter. Typical particulate fall-out in the United States amounts to approximately 11.5 million tons annually. The total particulate emissions level for Jacksonville, Florida, for example, is approximately 14,000 tons/year. This quantity of particulate amounts to a typical level of 30 to 90 tons/sq mi per month for urban areas of the country, or about 250 to 300 lb/acre per month. The 190 tons of Al_2O_3 evolved from each 156-in.-dia motor firing will give a particulate fall-out less than 100 lb/acre at the plant boundaries, assuming all 190 tons falls within the plant. During one of the 260-in.-dia motor firings at the Aerojet Dade Facility, 1 to 2 lb/acre fall-out was measured 5 miles downwind from the test site. In either case, the ground concentrations are significantly lower than normal particulate levels. In addition, Al_2O_3 is considered non-toxic to man and animals and does not exhibit phytotoxicity toward vegetation.

Extensive monitoring of the atmosphere using both ground and airborne sampling devices will be performed during testing. The results of monitoring during prior large SRM tests indicated that the exhaust products from the testing of motors containing propellant of similar compositon to that of the 156-in.-dia motors was not harmful to human life, plants, wild life, buildings, or equipment. The only claim pertaining to damage from a solid rocket motor firing within plant involved the firing of a 260-in.-dia motor with a unique propellant composition in June 1967. This motor, designated 260-SL-3, operated for 80 sec and developed a peak thrust of 5.9 million pounds. As a result of fall-out from this test firing, damage to citrus (lime) and avocado crops was sustained in groves located downwind (in a north-northeasterly direction) from the test site for a distance of up to about 20 miles. The crop damage took the form of small grayish-brown spots on the skin of the fruit that detracted from their market value.

II.B. System Studies (cont)

This crop damage was totally unexpected because Aerojet had previously conducted three static test firings of large solid rocket motors at the same test site without any fall-out problems. These motors included a 120-in.-dia motor containing approximately 200,000 pounds of propellant and two 260-in.-dia motors each containing 1.7 million pounds of propellant. In addition, hundreds of other solid rocket motors of many different sizes had previously been statically test fired at Aerojet's Sacramento, California facility without any evidence of off-site damage from the exhaust products.

The crop damage resulting from the Motor 260-SL-3 static test is believed to be attributable to a combination of two factors that were not present in any of the previous static tests at the Aerojet Dade facility:

a. The use of a new type of burning rate accelerator in the propellant loaded into Motor 260-SL-3.

b. Local weather conditions consisting of scattered showers, broken clouds at 1600 ft, and overcast at 8000 ft.

The new burning rate accelerator incorporated in Motor 260-SL-3 propellant formulation was a treated bentonite clay. The concentration of this burning rate additive was only 0.65 wt% of the propellant but, in a motor this size, it totalled more than 10,000 lb. Bentonite clay is a naturally occurring material with the capability of readily absorbing moisture. The decomposition temperature of this clay is very high and although it might have melted in the combustion process of the propellant, it was probably ejected in the exhaust and re-solidified with essentially no change in chemical composition.

As the cloud of exhaust products from the static test firing moved north-northeasterly under the influence of a 10-knot wind, it is probable that the particles of bentonite clay absorbed water and HCl vapor.

II.B. System Studies (cont)

These acid-containing particles, aided by the rain, were then precipitated on the crops. The clay itself could have caused the discoloration of the fruit, but more probably, the clay served to hold the very dilute solution of HCl in contact with the skin of the fruit long enough to cause pigment changes.

b. Launch Operations

No complaints have been received to date at any launch site because of solid rocket motor by-products. Measurements made at ETR during the first nine launches of the Titan IIIC vehicle showed no HCL outside the perimeter of the pad, which is estimated to be 600 ft in radius from the launch point.[3] Measurements only 50 ft from the launch pad indicated that in all cases there was no measurable HCl only 45 seconds after lift off, and in one case, it was zero only 14 seconds after lift off. This is apparently due to a tremendous thermal up-draft which carries away the HCl. The report draws the conclusion that no toxic hazards exist down-wind from the launch site.

The Al_2O_3 in the solid rocket exhaust stream of a shuttle launch (two 156-in.-dia motors) will merely add to the existing particulate fall-out in the vicinity of the launch site and down-range. If it is assumed that all the Al_2O_3 particles fall within a region one mile wide and 40 miles down-range from the launch pad, the resulting fall-out would be less than 10 tons/sq mi per launch. Even at a launch rate of 5 per month the Al_2O_3 fall-out will be within the range of the typical particulate fall-out of 30 to 90 tons/sq mi per month occurring in urban areas of the country.

II.B. System Studies (cont)

c. Long-Term Effects

A comparison of the exhaust gas emissions from the space shuttle SRM boosters with emissions from other sources is shown in Figure II-11. SRM exhaust products from a 440 flight shuttle program will contribute less than 1 percent to the nation's HCl emissions.

Despite the millions of pounds of HCl emissions each year, HCl is not a global air pollution problem. Once diluted and dispersed, HCl does not represent a persistent or toxic compound. On this basis, it does not appear that the modest contribution to atmospheric emissions of HCl resulting from SRM booster operation represents a significant environmental impact.

II.B. System Studies (cont)

5. Recovery and Reuse

a. Introduction

Recovery and reuse of SRM boosters is an option that promises significant cost savings for the Space Shuttle Program and can be accomplished with a re-entry deceleration system using parachutes and retro-rockets that will provide damage-free splash-down for the booster stage. Refurbishment and reuse of SRM components is common practice, even on units not designed specifically for reuse. The basic shuttle program of 440 operational flights can be accomplished with 15 production booster stages, each capable of 30 flights. It is estimated that this approach will reduce total SRM booster program costs by 30 percent.

b. Re-entry Deceleration

Although expended solid rocket motors have been observed floating in the ocean after several vehicle launches, supplementary re-entry deceleration devices will be required if routine recovery of SRM boosters is desired. It is difficult to predict the maximum water impact velocity that can be tolerated by an SRM without damage. Near the limiting velocity small variations in wave dynamics, entry attitude, or wind velocity could make the difference between no damage and severe damage. For this reason a conservative re-entry deceleration system is defined that will provide zero impact velocity under normal conditions.

Goodyear Aerospace Corporation has provided design information on a parachute system that is capable of decelerating a re-entering 156-in.-dia SRM to a terminal velocity of 100 ft/sec. According to Goodyear the weight and cost of the parachute system increases rapidly for terminal

II.B. System Studies (cont)

velocities below 100 ft/sec. This is confirmed in data provided by Lockheed Missiles and Space Company[(4)*]. On this basis 100 ft/sec was selected as the terminal velocity for the parachute system. The remaining deceleration is provided by a retro-rocket.

The Goodyear parachute deceleration system uses a 40-ft-dia drogue to provide the initial stabilization and deceleration of the SRM. The drogue is deployed by a pilot chute at an altitude of 25,000 to 30,000 ft and a dynamic pressure of 650 psf. The 16-ft-dia pilot chute is expelled by a mortar system. The drogue system is designed for tumbling re-entry of the SRM at 0.5 rps.

The main parachute package consists of two clusters each containing three 83-ft-dia chutes. The mains are deployed at an altitude of about 12,000 ft using a 20-ft-dia pilot chute for each cluster. The dynamic pressure at main chute deployment is 190 psf. A single stage of reefing is used to limit chute and SRM loads. Terminal velocity of 100 ft/sec is reached at about 4,000 ft.

The weight of the drogue and main chutes is 6,500 lb. Accessories and packaging will increase the total system weight to 7,500 lb.

A comprehensive parachute system DDT&E effort has been defined by Goodyear. The program includes extensive wind tunnel and drop testing.

The use of parafoils or parawings should be investigated prior to final selection of an aerodynamic deceleration system for the shuttle booster. Although parafoil/wing/sail technology is not as well developed as

* References are given in Section VI.

II.B. System Studies (cont)

parachute technology, there may be advantages in cost and weight that should not be overlooked.

A retro-rocket will provide the final deceleration needed to reduce the nominal SRM splash-down velocity to zero. For an SRM with an initial propellant loading of 1,000,000 lb the retro-rocket will weigh 2,600 lb and will contain 2,080 lb of propellant. The retro-rocket will be a 42-in.-dia by 85-in.-long solid rocket motor with a burning duration of 1 sec.

Initiation of the retro-rocket will be controlled by a radar altimeter with an accuracy of +10 percent. The SRM ordnance system logic and power supply can readily be adapted to handle the retro system requirements.

c. SRM Water Entry

The attitude of the SRM as it enters the water is an important consideration in defining impact loads resulting from splash-down. Four basic orientations were investigated.

(1) Vertical, nose down
(2) Vertical, nozzle down
(3) Inclined, nose down
(4) Horizontal

The vertical, nose down attitude has several advantages when used with the selected deceleration methods. The nose fairing of the SRM provides an ideal location for the retro-rocket and can readily be adapted for reacting the thrust loads into the case structure. The retro-rocket thrust vector will pass through the booster center of gravity and will result in maximum vertical deceleration. The nose down attitude also protects the nozzle

II.B. System Studies (cont)

and any TVC equipment from damage, and should result in a minimum amount of water entering the SRM case.

A potential problem with nose down entry is the external pressure load on the SRM resulting from penetration into the water. At impact velocities above 50 ft/sec the depth of SRM penetration would cause sufficient external pressure to buckle the case wall. However, this will not be a problem when using a retro-rocket deceleration system. Another stress condition that must be considered with vertical entry is that produced by toppling and slap-down of the SRM into the horizontal floating orientation.

With a vertical, nozzle down entry attitude the exit cone and aft support structure will act as a cushion or shock absorber. SRM penetration into the water will be less than for a vertical, nose down condition. However, impact loads on the nozzle and aft-mounted equipment may be a problem. Also, some water will enter the interior of the SRM. This will complicate subsequent recovery and refurbishment operations. As with nose down entry, the toppling and slap-down loads must be considered.

As inclined, nose down entry appears desirable if a retro-rocket system is not used. At higher impact velocities this orientation results in the lowest shock loading and restricts water penetration to acceptable depths. Slap-down loadings also are reduced. A 30 to 45 degree entry attitude relative to the water surface appears most favorable. Use of retro-rockets is difficult with this orientation, and parachute rigging is more complicated than with vertical entry.

Horizontal entry of the SRM induces loading conditions that are very dependent on impact velocity. Below about 20 ft/sec these forces will not be damaging to the SRM structure. The effect of wind-induced horizontal velocity is the least critical in this entry attitude, and there is no

II.B. System Studies (cont)

slap-down or toppling effect. The biggest disadvantage associated with horizontal entry is the necessary complexity of the re-entry deceleration system. Multiple retro-rockets are required and packaging problems will be severe. The rigging of the parachute system to provide for horizontal impact will be most complex.

Based on these considerations the vertical, nose down entry attitude was selected for further study. An analysis was made of the loads on the SRM with this entry attitude for water impact under the following conditions:

(1) Vertical impact velocity of 20 ft/sec
(2) Horizontal impact velocity of 30 ft/sec

These conditions represent nonoptimum deceleration system performance combined with a substantial wind-induced horizontal velocity. The inert weight at impact used in the calculations was 117,000 lb. The forces acting on the SRM are the result of:

(1) Vertical deceleration
(2) Lateral deceleration
(3) Hydrostatic pressure (external) from water penetration
(4) Toppling action due to rotation from the vertical attitude

Penetration of the forward section of the SRM into the water was calculated to be 319-in. At this depth the case buckling margin of safety is +1.74. Thus, a 20 ft/sec impact velocity will be no problem and 50 ft/sec could occur within positive margins of safety.

II.B. System Studies (cont)

Combined stresses from the initial vertical and horizontal impact are low and high margins of safety result. The most severe condition is encountered when the SRM rotates and impacts in the semi-horizontal mode. A conservative analytical approach was used in this calculation and a positive margin of safety was found to prevail.

It is therefore concluded that the selected water entry attitude at the conditions established will not damage the baseline SRM stage. However, it must be understood that this concept does not necessarily represent the optimum technique and additional detailed studies should be conducted. For example, at horizontal velocities higher than the 30 ft/sec considered, horizontal entry may prove more satisfactory although this approach complicates the deceleration system.

Detailed analytical results of the water impact study are presented in Appendix A.

d. Recovery Aids

After splash-down the SRM will float slightly nozzle down, at an inclination of about 2 degrees. This is because the SRM center of gravity is aft of the center of buoyancy in a horizontal attitude. In this condition there will be less than 1-ft of freeboard between the waterline and the lowest point of the nozzle throat. Wind and waves could easily drive water into the SRM. This will increase the inclination of the SRM and allow still more water to enter. The SRM will not sink because eventually the inclination will reach the point where the nozzle is submerged and no additional water can enter. However, the water in the SRM will make recovery and refurbishment more difficult.

II.B. System Studies (cont)

Two methods can be used to alleviate this problem. First, flotation devices can be provided to elevate the nozzle throat above the water. Second, a nozzle cover or seal can be deployed prior to impact to prevent water entry. We have selected the second method as most promising, but further study is needed.

Other recovery aids will include beacons and radar transponders to provide warning and to aid in locating the floating SRMs. In addition, fittings will be provided to allow attachment of gear for recovering and securing the SRMs.

e. SRM Design for Reuse

Three key areas must be considered in evaluating the reuse capability of an SRM:

(1) The SRM case must be designed to withstand the required number of operational and proof test pressure cycles (30 flights plus 30 proof tests for the shuttle booster).

(2) All components must be protected from corrosion and designed for refurbishment.

(3) The basic size of the recoverable stage must be increased over that of an expendable version to account for the added inert weight of the recovery system.

The baseline 156-in.-dia segmented SRM case design has been evaluated to assess its capability for withstanding 60 pressurization cycles. This D6aC steel case was designed to have a safety factor of at least 1.4 on ultimate strength when at maximum expected operating pressure (MEOP) of

II.B. System Studies (cont)

1000 psia. In addition, the case was designed not to yield at a proof pressure of 1.1 x MEOP. The hoop stress in the chamber at MEOP will be:

$$\sigma_{HM} = \frac{Pr}{t} = \frac{(1000)(78)}{(0.464)} = 168{,}100 \text{ psi}$$

while at proof pressure the hoop stress will be:

$$\sigma_{HP} = \frac{(1100)(78)}{(0.464)} = 184{,}900 \text{ psi}$$

The number of stress cycles that will propagate a flaw to failure has been shown by Tiffany[5] to be related to the ratio of the initial stress intensity, K_{Ii}, to the critical stress intensity, K_{Ic}. Stress intensity as defined by Irwin[6] is related to flaw size and operating stress by:

$$\sigma = 0.515\, K_I/\sqrt{a/Q}$$

where σ is the stress on the gross section, psi
a/Q is the normalized flaw depth, in.
K_I is the stress intensity, psi $\sqrt{\text{in.}}$

Hartbower[7] has found that K_{Ic}, the critical stress intensity at the onset of unstable, plane strain fracturing, for 0.475-in.-thick D6aC steel heat-treated to 220,000 psi ultimate tensile strength is 108,000 psi $\sqrt{\text{in.}}$ In addition, he has obtained cyclic loading data for D6aC steel. These data resulted in the failure loading boundary line shown in Figure II-12.

II.B. System Studies (cont)

For the specific baseline case design it is estimated that any flaw longer than 0.065-in. will be detected during NDT inspection. For this flaw size at the hoop stress occurring at proof pressure, K_{Ii} will be 33,300 psi $\sqrt{\text{in.}}$, and the ratio of K_{Ii}/K_{Ic} will be 0.308. Based on the failure boundary shown in Figure II-12, the life expectancy of the 156-in.-dia case segments will be in excess of 2,400 cycles. This represents a large margin over the planned 60 cycles to which each recoverable SRM segment will be subjected. Should further analysis indicate that additional cycling capability is needed, it could be achieved by reducing the case operating stress levels or by changing to a material such as maraging steel with a higher fracture toughness.

In the area of corrosion protection it will be necessary to use high quality protective coatings on all exposed surfaces. Clevis joints will be protected from salt water penetration. All electrical distribution boxes will be waterproofed and potted. Electrical connectors will be environmentally sealed.

The basic segmented case design provides for ease of disassembly and refurbishment. Nozzle liners will be bonded with room-temperature-curing epoxy adhesive to facilitate removal, clean-up of shell, and reinstallation of new parts. Liners will be interchangeable using gage point dimensioning. Premolded case insulation components will be readily removed and replaced.

The recoverable 156-in.-dia SRM configuration is shown in Figure II-13. The motor size has been increased by 4.7% to make up for the added inert weight of the recovery system. The effect on total stage weight and mass fraction is shown in Figure II-14.

II.B. System Studies (cont)

f. Recovery and Reburbishment

(1) Impact Area Operations

This phase has not been evaluated in depth during the current study, but the basic elements have been considered. Pick-up and retrieval of the spent stage and subsequent return to KSC may be accomplished by various means including.

(a) Barge with derricks
(b) Barge with open end and winch (whaler concept)
(c) Tow-back by tug

Although possibly more expensive, either of the barge concepts provide the advantage of enabling decontamination operations by fresh water wash to be started almost immediately after pick-up. Towing of the SRM back to KSC in heavy seas or in a stiff crosswind may be difficult. A technical and economic trade-off analysis is needed prior to final selection of the retrieval method.

(2) Disassembly and Preparation for Refurbishment

As shown in Figure II-15, the basic recovery plan involves return of the SRMs to KSC for disassembly. Following disassembly, some of the stage components remain at KSC for refurbishment. The basic SRM components are loaded onto the SRM transportation barges for return to the Aerojet Dade facility. An alternative approach would use ocean-going barges in a triangular pattern from Dade to KSC to recovery and back to Dade. This may have economic merit and should be studied further in conjunction with the retrieval methods evaluation.

II.B. System Studies (cont)

Return of SRMs from the impact point to KSC should take about 14 hr. Off-loading of the spent stage assembly can be conducted at a new facility adjoining the proposed MSIB and using a common docking arrangement. An alternative plan would be to locate this facility at or near the existing dock adjacent to the VAB. Included as a part of this facility would be:

(a) A 100-ton overhead bridge crane with sufficient hook height to lift the assembled boosters from the barge and position them on disassembly stands.

(b) A two-position vertical disassembly area, with the necessary access platforms and utilities.

(c) A segment clean-up and preservation area.

Aerojet activities at KSC in relation to the returning hardware will involve the following operations:

(a) Assist in the off-loading operation of SRMs from the recovery barge.

(b) Disassemble segments; removal all live ordnance, raceway covers, full length cables, exit cone, nose cone, and stage structural elements.

(c) Decontaminate and apply preservative to case sections and other items scheduled for reuse.

(d) Install handling and shipping tooling.

II.B. System Studies (cont)

(e) Assist in loading of case section and subsystems on the barge for shipment to the Aerojet Dade County manufacturing site.

Five hundred and twelve man-hours are required to accomplish the above operations for each set of two SRMs recovered. Equipment for segment handling and traffic will be available at KSC from motors in the launch preparation cycle. The recovery operation affords a convenient mode of recycling this equipment back into the Aerojet Dade facility. A minimum of additional special tooling or equipment will be needed.

(3) SRM Refurbishment Operations

Fired chamber segments will be received at the A-DD facility on shipping pallets. Transfer of the segments from the barge will be accomplished at the motor shipping facility. The segments will be moved on in-plant transport trailers to the refurbishment facility and positioned on vertical disassembly stands. Corrosion preventives and loose internal char will be removed by steam cleaning with detergent and steam rinsing. Disassembly of remaining stage hardware from each segment will then be accomplished. This disassembly will involve disconnection and removal of electrical and instrumentation items, thrust termination hardware, heat shield, TVC pumps, plumbing and actuators, the nozzle, flexseal, and the fired igniter. All of those subsystems and components destined for reuse will be transferred to the component refurbishment facility for further tear-down, inspection, test, and recertification.

The stripped-down chamber segments will be placed individually onto a roller fixture within an oven and heated to approximately 350°F. At this temperature the epoxy adhesive securing the internal insulation to the case is degraded to a soft gum and the insulation is easily removed.

II.B. System Studies (cont)

Based on experience, about 8 to 16 hr of heating will be required to degrade the adhesive. Removal of the insulation and most of the gummy adhesive will be achieved by rotating the segments while a mechanically moveable scraper is maintained in contact with the case. After insulation removal the machined metal surfaces will be masked and the segments positioned on a grit blasting fixture. This fixture consists of driven roller for rotating the chamber and a semi-automatic moving gritblast boom which can be positioned to follow the internal contour of the segments. The gritblasting operation will remove the residual epoxy adhesive from the case interior to expose a clean uncontaminated metal surface. Residual grit and dust are removed by vacuum cleaning and solvent washing.

The cleaned chamber segments will be positioned on a hydrostatic test fixture and tested to the required proof pressure. Dimensional and gage inspection of the refurbished chamber segments will be accomplished. Damaged or worn machined surfaces, holes, or threads will be repaired by use of dalic plating and polishing, or hole and thread inserts, as required.

Reinsulation of the chamber is accomplished by first abrading and solvent cleaning the premolded sections of rubber insulation. Next, application of epoxy adhesive and installation of the rubber sections onto the case is performed. Locating tooling is assembled to the chamber segments for correctly positioning the rubber sections and pneumatic pressure pads secure the sections during cure of the epoxy adhesive. Cure is accomplished by placing the insulated case into an oven at approximately 135°F. After cure, the tooling and pressure pads are removed and final dressing, grinding, and inspection of the insulated chamber segment is performed.

II.B. System Studies (cont)

(4) SRM Component Reusability Rates

Estimates of the reuse capability of SRM components were based on an assessment of each component's design characteristics, sensitivity to impact loads and salt water exposure, and the compatibility with refurbishment, inspection, and repair procedures. The selected reusability estimates are summarized below and were used to prepare the recoverable motor program cost estimates. The effects of booster recovery on program costs are discussed in detail in Section III.C.

Component	Reusability Rate, %
Case	100 (30 reuses)
Insulation	0
Nozzle	
Ablatives	0
Structures	80
Flexseal/TVC System	50
Stage Structures	
Nose Fairing	80
Attach Structures	80
Skirt Extensions	100
Aft Support Structures	100
Heat Shield	0
Ordnance	0
Instrumentation/Electrical	80

(5) Reliability/Quality Verification During Refurbishment

SRM components including case segments, TVC system, and structures will be subjected to a postflight reliability analysis to provide trend and verification data necessary for recertification. Major elements

II.B. System Studies (cont)

of the review will include insulation and nozzle ablative erosion profiles, ignition system integrity, and general structures and systems condition.

A damage analysis will be conducted to assign rehabilitation/replacement priorities to each major system and subsystem element. The data derived in this effort will be included in the reliability recertification program.

Quality verification will be conducted throughout the refurbishment cycles by inspection and quality engineering personnel. Disassembly operations and insulation removal will be monitored for critical process control of temperatures, soak mediums, time, abrasive cleaning, and weight loss. Dimensional, proof, and NDT techniques will be specifically applied to critical parameters to provide recertification data.

Each case segment will be proof tested at 1.1 x MEOP prior to recertification. Proof test tooling will be designed to provide dimensional verification of critical assembly interfaces during the test operation. Segments will be instrumented for retrieval of acoustic emission data during proof test. The purpose of monitoring acoustic emissions during proof test is to ensure that critical flaw growth does not occur. Flaws that grow during a particular proof cycle can be detected and located for further investigation by NDT techniques. If a defect is innocuous in terms of critical crack size, an additional cycle of service will be permitted. If the rate of flaw growth increases, or if the characteristics of the stress wave emissions indicate that the flaw is approaching critical dimensions, the defect must be repaired or the segment rejected.

Successful proof test at 1.1 x MEOP with no acoustic emissions indicative of critical flaw growth will assure that the subsequent cycle to MEOP can be accomplished safely. In the absence of slow crack growth

II.B. System Studies (cont)

such as that brought about by hydrogen embrittlement or stress corrosion cracking, there can be no subsequent failure at MEOP stress. Fracture mechanics analysis shows that the proof test confirms at least a 15 percent margin in critical flaw size at MEOP.

NDT of each segment will include magnetic particle and dye-penetrant inspection of surfaces, clevis features, and sealing interfaces. Radiographic inspection of welds is scheduled on the basis of segment fabrication/test history, acoustic emission results, dimensional growths and the other NDT procedure results.

Appendix B provides a description of typical SRM component recertification test procedures.

(6) Refurbishment Timeline

The SRM refurbishment timeline from splash-down to launch is shown in Figure II-16. The 90 day cycle includes a generous allowance for vehicle integration and launch preparations. A total of 15 boosters is required to support a peak launch rate of 60 missions per year. On this basis the recoverable booster program plan provides for 15 production booster stages. In addition the hardware from 6 DDT&E flights, together with 4 spare SRM's will be available to make up for any schedule slippage or booster attrition.

II. Technical Discussion (cont)

C. PRELIMINARY DESIGN

1. Stage Configuration and Performance

A baseline motor was selected for this study to provide a firm design point which could be analyzed in depth. The motor propellant loading of 1,000,000 lb is representative of the size required for several of the parallel or series burn vehicle configurations. The baseline stage configuration, shown in Figure II-17, is the parallel-burn RAO concept with a canted nozzle, but without thrust vector control or thrust neutralization systems, which were studied as program options. A maximum expected operating pressure (MEOP) of 1000 psia was selected for design purposes as being representative, but not necessarily optimum. A minimum design safety factor of 1.40 on ultimate strength was used for structural components. Safety factors of 1.5 to 2.0 were used for ablative insulation component design.

The two 320-in.-long center segments were sized on the basis of available lifting capacity for assembly in the VAB at KSC. Minimizing the number of segments has the effect of reducing cost and increasing reliability. Transportation studies showed the most convenient and economical shipping mode to KSC was by barge, so that rail shipment weight limits are not constraining.

The D6aC motor case is typical for segmented motors, using the pin-and-clevis concept at the segment joints, integral Y-ring stub skirts, and bolted joints for the igniter and nozzle attachments. The fixed ablative-lined nozzle is canted at 15 degrees to locate the thrust vector through the vehicle center of gravity, eliminating the need for a TVC system in this concept. The nozzle exit half-angle is 17.5 degrees and the expansion ratio is 10.

II.C. Preliminary Design (cont)

The propellant grain is a circular-port configuration with a star shape in the forward segment. The forward face of the aft segment grain is restricted, but the other grain ends are allowed to burn, providing a regressive thrust-time characteristic. The propellant is an 88% solids hydroxyl-terminated polybutadiene (HTPB) formulation. Insulation is a conventional butadiene acrylonitrile rubber system with silica and asbestos fillers. The ignition system is a solid propellant gas generator initiated by redundant exploding bridgewire (EBW) systems.

The stage structural components include the nose fairing, forward attach members, base support, and aft attach struts. The forward attach member ties the booster thrust into the ring frame between the hydrogen and oxygen tanks and provides lateral support. The base structure supports the vehicle weight on the ground through four locating pads and provides both lateral and roll support. The aft struts are attached to slip fittings on the HO tank with a hinge arrangement, which provides a rotation pivot and release during staging, so that no separation rockets are required. Also included in the stage components are a fully redundant EBW initiated destruct system and a complete instrumentation package.

The motor delivers a 40% regressive thrust characteristic over a 135 sec web action time, followed by a 10 sec tailoff, as shown in Figure II-18. The motor initial thrust at sea level is 2,244,000 lbf and the average operating pressure is 624 psia. Motor performance characteristics with estimated variance coefficients are summarized in Figure II-19. A weight summary, for the baseline configuration with options for thrust neutralization and thrust vector control, is presented in Figure II-20.

C2

II.C. Preliminary Design (cont)

2. Motor Case

The preliminary baseline chamber design incorporates use of D6ac steel conforming to Specification AMS 6431B. Minimum ultimate and yield strength values established for preliminary design are in accordance with the material specification, i.e., 220,000 psi minimum ultimate and 190,000 psi minimum yield. The steel is produced by the vacuum consumable electrode remelt process to obtain clean and homogeneous material with good fracture toughness and fatigue strength properties. The material is readily available and has been demonstrated to be reproducible and reliable through extensive past and current use in solid rocket motor chambers. To assure use of material with adequate fracture toughness, a minimum fracture toughness value will be specified as an accept/reject criterion for material procurement.

The 18 percent nickel, 200-grade, maraging steel was evaluated on a preliminary basis for fabrication of 156-in.-dia motor cases. The 18 percent nickel steel is a good structural material candidate but was not considered economically competitive with D6ac steel in the baseline program. The 18 percent nickel material should be considered in any subsequent evaluations that may involve smaller quantities of production units or other considerations affecting material selection.

The baseline case consists of 4 segments (2 center segments) connected by pin-and-clevis segment joints. The 0.464-in. minimum cylinder wall thickness is sized to provide a safety factor of at least 1.4 on ultimate strength at an MEOP of 1000 psia. In addition, the case is designed not to yield at a hydrostatic proof pressure of 1.1 x MEOP. A biaxial gain factor of 1.13 was used in designing the cylinder membrane. Cylinder girth weld reinforcements 0.50 to 0.55-in.-thick are provided to reduce weld stresses in the welded chamber configuration for added reliability.

II.C. Preliminary Design (cont)

The nozzle and igniter attachment bosses are conventional designs that have been highly successful in extensive use in operational solid rocket motors such as the Minuteman ICBM. The forward and aft skirts are integrally machined from forged subassembly components and provide mechanical attachment provisions for the forward nose fairing and the aft support structure.

The pin-and-clevis segment joint is a conventional design concept successfully demonstrated in many static firings and flight launches of the Titan vehicle. The straight-pin concept was selected and is shown in the preliminary baseline case design. However, both the straight-pin and tapered pin segment joint concepts should be evaluated in more detailed design analyses and trade studies before making the final design selection for specifically defined motor requirements.

The 156-in.-dia case can be conveniently fabricated by substitution of segment joints in place of welds in the cylinder section; and, by incorporating a mechanical joint similar to the nozzle joint in the forward head subassembly. The flexibility that exists with either welded or no-weld chamber construction results in significant growth potential for the motor.

3. Nozzle Assembly

The baseline nozzle is a fixed type design as shown in Figure II-21 and is canted 15 degrees from the motor axis by rotating the nozzle about the geometrical center of the spherical aft dome. In this way, both a symmetrical nozzle and symmetry of the motor case are maintained. The nonsymmetry resulting from the cant angle is incorporated into the spherical nozzle shell. Assembly of the nozzle to the motor case is through a 135-in.-dia bolted joint.

II.C. Preliminary Design (cont)

The nozzle has a submerged configuration to minimize unsymmetrical gas flow at the entrance regions of the nozzle. To meet motor performance requirements, a 48.1-in. throat diameter and a 10:1 expansion ratio were selected. The entrance contour is a 3:2 ellipse with the nose station at an area ratio of 2.0. A conical shape with a 17.5 degree half angle is used for the divergent section. The length of the nozzle from the throat station to the exit plane is 168.7 in.

The nozzle is comprised of three subassemblies which are mechanically attached to each other through bolted joints. In the nozzle throat assembly, an AISI 4335 steel shell forms the spherical closure and also provides structural support for the ablation liners in the throat and submerged sections. Glass fiber and epoxy resin composite is the material for structural support of the liners in the low pressure regions of the forward and aft exit cone assemblies.

Materials for the ablation surface liners were selected to meet the thermal and erosive environments of the exhaust gas. The selected materials have been characterized on other programs and specifications are generally available for the control of the material quality. High erosion resistant carbon cloth phenolic is used at the throat and entrance sections of the nozzle. Pluton B-1, which is an 87 percent carbon fabric with amounts of boron, phosphorus, and nitrogen, is used on the backside of the nozzle submerged section, as well as on the exit cone up to an area ratio of 2.8:1. The low cost, less erosion resistant canvas phenolic is adequate for the environment conditions at the high (>2.8) area ratios of the exit cone. The performance characteristics of these material systems were established from evaluation tests conducted under recently completed NASA programs (Contracts NAS3-12038 and NAS3-12064).

II.C. Preliminary Design (cont)

Using previous test data as the basis, the erosion and char depth of the nozzle liners were predicted from heat transfer analysis. The total liner thickness used in the nozzle design includes a safety factor on the predicted erosion and also limits the temperature use to the structural components. For the ablative liners at the low area ratio regions, the minimum liner thickness is the sum of twice the predicted erosion plus the predicted charred material thickness. In addition, an insulative material is provided on the backside of the liner so that no temperature rise occurs on the structural shell for the entire motor duration. For ablative liners at the high (>2.0) area ratio regions, the minimum liner thickness is the sum of 1.5 times the predicted erosion plus the predicted charred material thickness. Additional structural reinforced plastic material is used in this region to maintain a minimum safety factor of 1.25 on all loads.

State-of-the-art methods are used in the fabrication of the nozzle components and assemblies. Process specifications are available that define and control the procedures for welding of the steel shell, as well as for the tape wrapping, curing and assembly of reinforced plastic nozzle components. The steel shell is fabricated by welding of sections which are machined from ring-rolled forgings. The shell is subsequently heat-treated to attain a minimum yield strength of 190,000 psi. Final machining of the shell is made after welding and heat-treatment. Attachment flanges for joining between the nozzle subassemblies are machined from normalized AISI 4130 ring-rolled forgings.

Ablation liners are tape wrapped and autoclave cured. The tape orientation in each component is selected on the basis of proven performance in similar nozzle locations. These orientations are 0, 87, and 45 degrees to the nozzle centerline for the nose, entrance, and throat inserts, respectively. The submerged and exit cone liners have the tape oriented parallel to

II.C. Preliminary Design (cont)

the nozzle centerline. The insulative material, either canvas or glass phenolic, that overwraps the liner has a tape orientation generally parallel to the bonding surface.

The ablation liner and insulative overwrap are final cured simultaneously with autoclave pressure and 300°F temperature. The inserts of the nozzle throat assembly are cured with 425 psi pressure, while exit cone liners are cured with 225 psi pressure. The cured throat assembly inserts are machined and bonded to the steel shell with ambient temperature curing epoxy adhesive. Circumferential joints between inserts are filled with an ambient temperature curing silicone rubber.

The OD surface of the cured exit cone liner is machined and glass fiber impregnated with epoxy resin is laid up on the machined surface and cured at room temperature. Steel flange rings are bonded in place and reinforced with glass-epoxy roving.

Nondestructive techniques have been developed for inspection of the nozzle components and assembly. Ablative inserts are inspected by the tangential radiographic method to detect internal defects such as delaminations, voids, and changes in density. The ultrasonic technique is used to detect unbonded areas at the bonding surfaces between the steel shell and the nozzle inserts.

4. Insulation

The internal insulation system, as shown in Figure II-22, was designed to a conservative safety factor of 2.0, using silica and asbestos-filled butadiene acrylonitrile rubber (Gen-Gard V-44 and V-45 or equivalents). These standard insulating materials have been used on nearly all large SRMs.

II.C. Preliminary Design (cont)

The rubber is obtained as calendered uncured sheet stock and is laid up either in molds for curing and secondary bonding to the case, or directly to the prepared case surface for in-place vulcanization. A combination of premolded components and case-vulcanization will be used for the 156-in.-dia SRM.

The forward closure insulation has a design thickness of 1.52-in., since full or nearly full duration exposure occurs over most of the surface. The segment joints are exposed similarly under relatively static flow conditions and are designed to the same thickness of 1.52 in. The center segment insulation thickness tapers from each end over a distance equal to the grain web to a thickness of 0.25-in. for the remaining sidewall, which is only exposed during tailoff. The sidewall thickness is particularly conservative (a loss rate of 5 mils/sec would be the worst performance expected) to allow for within-grain burn rate variance, grain flaws, and static test afterburn, and will provide assurance of case reusability. In the aft segment, the insulation is used to provide the forward face restriction. The sidewall thickness of 0.25 in. tapers to a maximum of 3.00 in. at the nozzle closure joint, where exposure time and gas flow conditions are the most severe.

At the segment joints, the insulation is machined to a close tolerance relative to the steel interface to provide a compression-fit butt joint. At the igniter boss and the aft closure, the mating insulation components are machined to allow a slight gap which is filled with silicone rubber potting on assembly.

5. Propellant Grain

a. Selected Configuration

The propellant grain for the baseline motor is a modified circular-port configuration with a 49-in. web. The center segment ends are

II.C. Preliminary Design (cont)

allowed to burn, helping to neutralize the progressive geometry. The aft segment grain is restricted at the forward end to provide the necessary surface area at web burnout for a nominally 40% regressive thrust-times characteristic. The forward segment grain is an eight-point star with a 12-in. web, providing highly regressive burning surface areas. The circular port in the center and aft segments is tapered to induce a tailoff sliver for controlled staging. The aft segment port is shaped to the gas flow at the nozzle to align entrance.

b. Propellant

The selected propellant formulation, designated ANB-3400, contains 68 wt% ammonium perchlorate, 20 wt% aluminum and 0.15 wt% iron oxide. The aluminum content was selected on the basis of maximum performance with respect to delivered specific impulse and density. The binder is based on the low cost R-45M HTPB (hydroxyl terminated polybutadiene) prepolymer cured with TDI (tolylene diisocyanate). It is estimated that the target burning rate can be achieved with an oxidizer blend composed of 80% unground and 20% MA ground (Mikroatomized, 6 to 10 microns) ammonium perchlorate.

The estimated standard specific impulse to this propellant is predicted to be greater than 250 lbf-sec/lbm delivered at the mass flow rate of the baseline motor. The chamber flame temperature is approximately 6100°F.

The most important advantage of HTPB propellants compared to other propellant types (such as PBAN) is the superiority of processing characteristics. Properly formulated, HTPB propellants have near-Newtonian flow characteristics. This type of flow characteristic assures casting of sound motors free from grain and bond defects. PBAN propellants have demonstrated a pseudoplastic type of non-Newtonian flow characteristic in which the viscosity increases at low shear stress. If this departure from Newtonian flow is great enough, grain and bond defects will result.

II.C. Preliminary Design (cont)

The mechanical properties of HTPB propellants at 88 wt% solids are very good, and in fact are superior to PBAN propellants containing only 84 wt% solids loadings. Because the lower viscosity prepolymer permits higher solids loadings, HTPB propellants can be formulated to yield higher performance than PBAN propellants while maintaining adequate processing and mechanical properties. This higher performance, including both higher specific impulse and higher density, has a cost impact since less propellant is required in the motor for given total delivered impulse. The raw material costs for ANB-3400 are comparable to PBAN propellant.

The stability characteristics of HTPB propellants have been shown to be significantly better than CTPB propellants such as the ANB-3066 which is currently used in the Aerojet Minuteman III Stage II motor. This motor has a demonstrated storage life in excess of seven years. Based on this comparison the storage stability characteristics of ANB-3400 will be more than adequate.

Aerojet has been working with HTPB propellants for more than eight years, longer than anyone else in the industry. More than five million dollars in contract and Company-sponsored funding has been spent. This includes an 18 month NASA sponsored program for a contract (NAS3-12061) specifically directed at formulation of HTPB propellants for large booster motors. Aerojet is also currently producing under NASA contract the Astrobee "D" sounding rocket which uses a R-45M HTPB propellant.

As an alternative, the PBAN propellants offer the advantage of a history of reliable use in the solid rocket motors, and have been used in all very large solid rocket motors built to date. Aerojet has had extensive experience with PBAN propellants starting with the 260-in.-dia motor program in 1963. The ANB-3105 formulation used in the first two 260-in.-dia motors

II.C. Preliminary Design (cont)

meets the baseline motor requirements with a slight adjustment to the lower burning rate. The oxidizer content of 69 wt% would be a blend of 70% unground, and 30% MA. The iron oxide content would be 0.50 wt% and the aluminum content would be 15 wt%.

c. Ballistic Performance

The ballistic performance of the baseline 156-in.-dia SRM was summarized previously in Figure II-19. The thrust- and pressure-time histories are shown in Figure II-18.

The variance figures given in Figure II-19 are taken from earlier studies and are probably unnecessarily conservative. Comparison with actual data for the Titan IIIC SRM indicate that substantial improvements can be expected. However, the Titan IIIC between motor variances are not truly random in that selection of segments and motor pairing options are available. Further studies of variances and the effect of selectivity are continuing to realistically define this important aspect, since thrust mismatch is critical in defining vehicle control requirements.

d. Structural Analysis

A preliminary structural analysis was performed to estimate the structural requirements for the propellant grain and bond system and to determine if release boots will be required on the various segments. For the purpose of this analysis the grain was assumed to be fully case bonded. To improve the bond stress condition at the segment ends, however, a two-inch deep stress relieving groove was considered to be cast or machined in the end of each segment. This type of bond termination point design (Figure II-23), has been found to be effective in reducing the peak bond stresses associated with abrupt bond terminations.

II.C. Preliminary Design (cont)

The two conditions considered in this preliminary evaluation were vertical storage at 40°F and vertical launch at 60°F.

In estimating thermal stresses the grain was assumed to be stress free at the maximum cure temperature of 115°F and for firing the maximum initial pressure was taken as 1000 psia. The total storage time in the vertical position was estimated as six months and the launch acceleration was conservatively taken as 2.0 g.

The ANB-3400 propellant proposed for this application has not yet been characterized for mechanical properties but its structural characteristics have been estimated as being very similar to those of propellant ANB-3346-1. The latter formulation has been well characterized and is used in the Astrobee D sounding rocket motors.

A finite element model was constructed for a 320-in.-long center segment and, using the material properties for ANB-3346-1 propellant and V-44 rubber, computer solutions were run for both thermal and pressurization loadings. Due to the size of the segment, the gridwork used was necessarily quite coarse. To obtain a better definition of the stresses in the vicinity of the bond termination point, a second model was constructed to represent that local area.

The computer program used for this work considers the actual material to be represented by an assemblage of rings of cross-section as indicated by the finite element model. These rings are assumed to be inter-connected at their nodal points and the stress and strain within any given ring or "element" is considered to be constant. Using appropriate boundary conditions and loads, a set of simultaneous equations is then generated that express the deflection of each node point in terms of known and unknown

II.C. Preliminary Design (cont)

loads. The solution of this set of simultaneous solutions provides the actual nodal point displacements throughout the gridwork and permits calculation of stress and strain distributions as well.

In evaluating the local stresses around the bond termination point the displacements obtained from the coarse grid solution of the complete segment were used as boundary conditions for the smaller model.

The local strains in the forward end slots were estimated from a preliminary design procedure in the Aerojet Procedures and Methods Manual. This procedure involves computing the strain for a cross-section of equivalent web and increasing it by a geometrically determined concentration factor.

The acceleration or gravity stresses were determined from parametric curves which were generated from a series of computer solutions.

The maximum stresses and strains obtained from the above analyses occur in the center segments and are summarized in Figure II-24. In addition to these calculated requirements, corresponding allowables for the proposed system have also been estimated and margins of safety have been computed. The allowable strains are based on ANB-3346-1 propellant and the bond allowables are based on the tensile strength of the ANB-3346-1 propellant bonded to an SD 878 liner system. As can be seen in Figure II-24 the requirements are generally quite low with respect to the estimated allowables and no boots would appear to be necessary.

In determining the storage stresses on the bond, the atmospheric pressure environment in which the motor will be stored was considered. Due to the relatively low stiffness of the propellant in comparison to the case this has the effect of causing a compressive force across the bond

II.C. Preliminary Design (cont)

approximately equal to the absolute value of the atmospheric pressure. This results in the tensile stresses due to thermal shrinkage and gravity being reduced by approximately 14.7 psi as indicated in Figure II-24.

6. Igniter

The 156-in.-dia SRM ignition system, shown in Figure II-25, features the following pyrotechnic train:

a. Initiator

Dual exploding bridgewire (EBW) iniators will be mounted into the forward end of the ignition motor booster to provide the pyrotechnic train stimulus.

An alternative component which will provide the desired safety features is the Minuteman Weapon System Standardized KR80000-09 safety-and-arming device. This device meets the requirements of AFETRM127-1. Two ES-003 initiators contained in the S/A rotor provide the pyrotechnic train explosive stimulus.

b. Booster

The ignition motor booster will be a Minuteman Wing VI Stage II igniter. The booster initiator, which interfaces with the EBWs contains 37 grams of 2D-size boron-potassium nitrate (BPN) ignition pellets. Output from the booster initiator will ignite 3.3 lbm of ANB-3066 propellant, which is vacuum cast into an insulated and lined steel case. To date, the Minuteman Wing VI Stage II igniter has an observed reliability of 100% in 259 motor firings under all specified environmental conditions.

II.C. Preliminary Design (cont)

c. Ignition Motor

The ignition motor contains 153 lbm of ANB-3400-1 propellant, secondarily bonded into a D6ac steel chamber. The planned HTPB igniter propellant will be the same basic formulation as that used in the SRM, except the burning rate will be increased to 0.6 in./sec at 600 psia. The exterior and interior surfaces of the ignition motor chamber will be insulated to prevent melting or ejection during motor operation. The combustion products will exhaust through three equally spaced, 45 degree canted sonic nozzle ports in the aft closure.

An ignition system data summary is shown in Figure II-26. A predicted ignition transient analysis is presented in Figure II-27. The expected ignition interval* is 0.260 sec, and the expected 3-sigma ignition interval variation is approximately $\pm$ 0.060 sec. This ignition concept has been demonstrated in 156- and 260-in.-dia motor tests, and in the Titan IIIC SRM.

7. <u>Ordnance Systems</u>

The stage ordnance includes ignition, thrust neutralization, command destruct and ordnance distribution logic systems. A schematic diagram of the ordnance distribution concept is shown in Figure II-28. The design and selection of ordnance concepts for the SRM shuttle application are based on the performance and reliability of these concepts demonstrated in Minuteman, Poseidon, Saturn, and Titan III applications.

To provide safety against stray or inadvertant voltage inputs and to render the ignition system inoperative until launch power is required,

* Ignition interval is the time from firing unit capacitor discharge to 75 percent of motor initial steady state operating pressure.

II.C. Preliminary Design (cont)

dual Saturn-qualified Model R1-2B exploding-bridgewire (EBW) initiators will be mounted into the forward-end of the ignition motor booster to provide the pyrotechnic train explosive stimulus. The high voltage, high current firing pulse for the EBW initiators will be provided from two electrically redundant firing units. A block diagram of a typical EBW firing unit is shown in Figure II-29.

The thrust neutralization system ordnance will consist of the following components:

a. Safety

Thrust termination will incorporate the redundant EBW system previously described for the SRM ignition system, except EBW detonators will be used in place of initiators.

b. Transfer Harness

The transfer harness will be a sheathed 70 grain/ft RDX core. The harness receives the EBW detonator output in the crossover manifold and transfers the explosive stimulus to the flexible linear shaped charge (FLSC). The transfer harness will be comprised of two redundant cores, with appropriate crossovers for additional reliability.

c. Cutting Charge

The FLSC provides the explosive force required for cutting the motor forward dome. It provides an extremely directional jet of high velocity particles and results in a clean cut in the dome. Two redundant cutting charges will be mounted in a forward dome retainer.

II.C. Preliminary Design (cont)

The command destruct (CD) system will use redundant EWB detonators, transfer harness, LSC, and jumper harness.

The CD system functions only on command signal from the core vehicle. These connections are made through the stage disconnect. The exact details regarding CD system function or necessity cannot be defined at this time, since the specific range safety requirements are not known. However, the CD concept is included for planning purposes, and to indicate the function of such a concept if required.

The CD system will consist of the following ordnance components:

a. Safety

Same as TN System.

b. Transfer Harness

Same as TN System.

c. Cutting Charge

Single run of dual LSC strands.

d. Jumper Harness

A jumper explosive core, identical to the transfer harness, will be installed to propagate the explosive stimulus from one segment to the next.

II.C. Preliminary Design (cont)

The destruct system consists of a single run of LSC (dual strands) attached to the exterior of the motor casing.

The LSC is housed in shield mount with slots for mating to prewelded mounting taps on the motor casing. Cabling raceway space has been left open between the two runs of LSC. A cover plate would cover the cabling and raceway interior. This cover is readily removable for inspection/ repair without interfering with the LSC assemblies. An alternative installation would be to adhesively bond the LSC assembly to the motor casing as is done on the Saturn S-1 destruct system. The LSC section proposed is keyed to 8-ft sections.

The LSC core load will be adjusted to ensure propellant rupture with adequate penetration. Dual strands of LSC are used to ensure redundancy. However, either run of LSC is sufficient to adequately destruct the booster. The destruct function can be accomplished between orbiter separation and 140 sec after ignition. This all-ordnance destruct concept has been demonstrated in Minuteman, Titan IIIC, and Apollo-Saturn applications.

Ordnance electrical distribution logic will be controlled from the SRM stage, through discrete signals received from the orbiter. Power input for ignition, TN, and CD can be supplied either from the orbiter, or from an ordnance battery contained in the SRM nose section, as shown previously in Figure II-28. For the purpose of this study, ordnance power is supplied from an ordnance battery in the SRM, and all control circuitry is located in the ordnance distribution section, actuated by signals from the orbiter. A summary of ordnance input and return signals required between the orbiter and the SRM is shown in Figure II-30 for both an EBW initiator/detonator system and for ordnance with safety-and-arming devices.

II.C. Preliminary Design (cont.)

8. Stage Structures

a. Nose Fairing and Forward Attach Structure

The vehicle forward attach structure provides the structural members for transferring support and flight thrust loads between the core HO tank and the SRM booster. The load carrying system is comprised of two high strength fittings which transmit support and flight loads to a common point on the HO tank. These members react loads into the ring structures contained in the nose fairing and into the cylinder section of the SRM case.

The load carrying members (Figure II-31) are fabricated using AISI 4340 steel, or equivalent, heat-treated to an ultimate strength level of 180,000 psi. This material-strength level combination provides maximum strength and toughness with accompanying rigidity, ease of fabrication, and minimum weight. The lateral thrust member is a single forging of minimum weight and cross section which is designed to distribute side loads of up to 233,700 lbf over a 90 degree arc of the nose fairing. Attachment to the HO tank is through a pin and clevis arrangement.

The axial thrust structure also is fabricated using AISI 4340 steel or equivalent heat treated to 180,000 psi ultimate strength level. This structure is composed of 5-in.-dia tubular members which mechanically attach to the chamber forward skirt extension and in turn, mechanically attach to a pin and clevis forging for SRM-to-tank attachment. The tubular sections are fabricated by inert gas, tungsten arc welding to end flanges prior to heat treatment; all welds are X-ray, magnetic particle, and ultrasonically inspected. The pin and clevis attachment forging contains no welds and has been designed for optimum grain flow in relation to design loads. The main thrust and support structure has been designed for a 2,337,000 lbf thrust load; these loads are transmitted over a 180 degree arc on the SRM forward skirt extension to a common attach point for the lateral thrust structure.

II.C. Preliminary Design (cont)

The SRM cylindrical skirt extension is fabricated of AISI 4130, HY-100, or equivalent steel alloy heat treated to 90,000 to 100,000 psi ultimate strength level. Two main members comprise this assembly. The cylinder extension is a ring rolled forging while the box structure is either mechanically assembled or welded using angle plate sections. For maximum reliability, welding is not permitted after heat treatment unless HY-80 or HY-100 class steels are used; all welds are X-ray, ultrasonic, and magnetic particle inspected. The box section is mechanically attached to the cylinder section which in turn is mechanically attached to the SRM forward skirt. The assembly has been designed to distribute thrust and side loads of 2,337,000 and 233,700 lbf, respectively, over a cylindrical arc of 180 degrees.

The nose fairing is of high strength aluminum alloy (Type 7075-T6 or equivalent) sheet construction, stiffened by internal rings. The conical configuration terminates in a spherical nose fairing. This design results in a suitable aerodynamic shape, and reacts the shear loads imposed by the lateral thrust fitting. The shell is designed to sustain an external pressure of 650 psf. No welding is used; the unit is mechanically assembled including all box structures. The box structure of "I" beam is designed to carry an in-plane load of 233,700 lbf. The nose fairing is mechanically attached to the SRM forward skirt extension and incorporates a fairing at this location for minimum aerodynamic drag at the SRM tank thrust fitting attachment point.

b. Vehicle Support and Aft Attach Structure

The vehicle support structure (Figure II-32) consists of two segments, a cylindrical adapter to the chamber stub skirt and a flared support skirt. The aft support skirt provides ground support of the vehicle on the launch platform and, in flight, acts as an aerodynamic fairing for the vectored or canted nozzle and all the aft end subsystems. The geometry of the

II.C. Preliminary Design (cont)

flare was selected to satisfy the basic requirements of adequate launch platform support and lift-off clearances, minimal aerodynamic drag and suitable space for the SRM subsystems (principally the TVC system). The design loads are based on 1 g static ground condition in addition to full orbiter engine thrust prior to SRM ignition. (A 40 mph static wind condition with empty core was investigated and is less critical.) The design is based on pre-lift-off axial and side loads of 2,520,000 lb and 410,000 lb, respectively. Flight loads are considerably lower.

The aft support skirt is a low alloy steel (Type AISI 4340, HY-80, or HY-100 steel or equivalent) column-truss arrangement framed by two box rings. Alternative designs such as aluminum honeycomb or a monolithic steel cone structure were investigated but discarded based on cost or weight considerations. The box structures are fabricated using HY-80 or HY-100 steel alloys heat treated to 100,000 psi ultimate strength. Both mechanical and welded assembly techniques can be used because both alloys are weldable in the heat treated condition with proper processing controls. All welds are X-ray, magnetic particle, and ultrasonic inspected to ensure maximum reliability.

The columns are fabricated using 4.5-in.-dia AISI 4340 seamless tubing (0.375 in. thick) heat treated to 180,000 psi ultimate strength level. Flanges for mechanical attachment to the box structures are welded to the tubing prior to heat treatment. An 0.032-in.-thick corrugated aluminum (Type 6061 or equivalent) nonstructural fairing is used to cover the aft support skirt structure. The eight vehicle support points are located at a 30 degree angle from the SRM centerline to provide a more effective moment arm for resisting the orbiter induced pad loads.

Roll and staging members are pin-end attachments to forged clevis fittings on the support skirt. These members are fabricated using AISI 4340 steel or equivalent heat treated to 180,000 psi ultimate

II.C. Preliminary Design (cont)

strength level. Tubular sections are welded to end attachments prior to heat treatment. The roll bars are attached to the support skirt upper ring, while the staging members are attached to the support skirt lower box ring. The members are designed for roll and staging loads of 345,000 lb and 173,000 lb, respectively. The attach fittings on the support structure are also of AISI 4340 steel (180,000 psi ultimate strength) and are mechanically attached to the box sections.

9. Instrumentation

a. Approach

Instrumentation system requirements for an SRM with a fixed nozzle (no TVC) are very simple. Other than the engineering data parameters that will be monitored on the early flight tests, only SRM chamber pressure measurements (3 channels) and ordnance functions are included in the baseline system.

Thus, the basic system consists of the following:

Pressure Transducers (3)
Signal Conditioning and Multiplexing Module (1)
Cable harness with Booster/Orbiter Interconnect
Monitoring network (bi-level voltage signal) for ordnance status indications

Electrical power for the SRM data system will be supplied from the orbiter (10 vdc regulated and 28 vdc). Ordnance firing voltage supply (battery) will be provided on the booster. Arm and fire commands will originate in the orbiter and will be transmitted in a cable harness isolated from the data buss.

II.C. Preliminary Design (cont)

The data acquisition system described in the subsequent sections is typical of a TVC system is included on the booster. The system is based largely on the Titan III instrumentation data system which has been operational for some 6 years and provides the best source of flight-rated components for the SRM operating environment. Updated state-of-art digital techniques are currently being used in both military and commercial aircraft systems and provide an attractive option which should be further investigated.

b. SRM Data Acquisition System

The SRM data acquisition system (Figure II-33) is based on the Titan III modular multiplexer - central converter configuration. Data multiplexing is provided at both the forward and aft sections to minimize cable runs. Baseline or "fixed" instrumentation is modularized separate from removable or "drop" instrumentation which would be incorporated only on the early development flights. Data channel requirements for both systems are summarized in Figure II-34.

In the digital system, modular transducer kits interface with the signal conditioners at the remote multiplex units. Data monitoring instrumentation will require a 86 channel remote multiplexer (and signal conditioner) aft and a 40 channel unit forward. "Drop" instrumentation will include a 46 channel RMU aft for digital data and 26 channels of vibration and acoustical (analog) data. The high frequency system will consist of integral amplifier/accelerometers and acoustic transducers located both fore and aft and an FM/FM subcarrier oscillator unit located in the transmitter compartment.

c. SRM Transducer Kit

The transducer types and manufacture, cabling, and interface connectors are essentially those of the Titan III Liquid Rocket engine.

II.C. Preliminary Design (cont)

The transducer components are used both on the 120-in.-dia SRM and the Titan air-frame.

The transducer cabling interface consists of modular interconnecting boxes which terminate 12 (18 thermocouple) twisted, shielded, cables and provide both an instrumentation and checkout interface connector. Pressure and resistance temperature transducers or strain gauges require a standard 6 wire cable (two shunt calibration leads). Chromel-alumel thermocouple cables are standard, but thermocouples of various types and numbers can be provided at the box level. A typical kit installation provides 32 channels of pressure, RTT, or strain gauge (4 bridge wire) measurements, 8 thermocouple, and 2 frequency (pulse) monitoring channels.

d. Remote Multiplexer/Digitizer Equipment

The converter bit rates shown in Figure II-33 are based on the estimated sample rates of Figure II-34 and an 8 bit analog data word. Approximately 33% of the Titan III converter capability is required by the SRM. The Titan converter unit operates at 384,000 bits/sec and with up to sixteen, 32 channel remote multiplexer units (RMU) connected. The converter unit programs sampling times of the RMU inputs and generates PCM data to the RF link. Each analog channel must have a low pass input filter (400 Hz corner frequency) and provide differential input. Signal conditioning equipment is physically a part of each RMU. The RMU's and converter units are manufactured by Space Craft, Inc., Huntsville, Alabama.

The Space Craft Inc. system can be readily adapted to the SRM, but to meet the requirements of the booster only, an updated, "scaled down" system could save weight and provide greater flexibility. It is doubtful, however, that significant cost savings would accrue. Other flight data acquisition

II.C. Preliminary Design (cont)

systems investigated included the Space Craft P50 System and the Teledyne Aircraft Integrated Flight Test Data System (AIFTDS).

The SPI P50 system is similar to the Titan III system but smaller (256 K BITS/sec). The system has been operational for some 3 years on the Agena Program. Improvements include plated wire memories, random access, and a 30% decrease in weight over older systems.

The AIFTDS remote multiplexer digitizer unit (RMDU) combines the functions of signal conditioning, multiplexing, digitizing, PCM data generation and transmission within a single box. Flexibility includes programmable gain and overscale control and automatic checkout of transducers (continuity of bridge and TC wires). The RMDU is a 64 channel, 128,000 WPS (1.5 megabits) miniabits) miniaturized version of the larger AIDS, which is now operational on aircraft.

e. Frequency Division Multiplexing

The Inter-Range Instrumentation Group (IRIG) Document 106-66 (1966) lists 29 FM proportional-bandwidth and 35 FM constant-bandwidth subcarrier channels. Combinations of both proportional and constand bandwidth channels may be used, the selection and grouping depending upon data bandwidth requirements (and guard band considerations). For the SRM frequency response requirements, it is estimated that use of the constant-bandwidth channels will provide higher quality data, however, final selection must await coordination of the particular range requirements.

10. <u>Thrust Vector Control System</u>

The selected thrust vector control system for the 156-in.-dia SRM is a movable nozzle incorporating an aft-pivot flexible seal. The flexible

II.C. Preliminary Design (cont)

seal is designed for ± 5 degree deflection capability with a seal rotation torque of 80,000 ft-lb. Although a flexible seal with the pivot point located either forward or aft of the nozzle throat plane can be designed to meet the TVC requirements, the system torque of a forward pivot seal must consider the internal aerodynamic torque to be additive to the seal rotation torque. For an aft pivot flexible seal design, the internal aerodynamic torque acts opposite of the seal rotation torque and is generally neglected in system torque considerations. For the purposes of this study, it was assumed that the seal rotation torque is higher than the internal aerodynamic torque and an unstable condition does not exist. This is a reasonable assumption, based on similar systems, but requires a more detailed analysis.

The flexible element of the seal is composed of 12 rubber layers and 11 spherical steel shims, as shown in Figure II-35. The contour of each element has a common pivot point which is located 23.7-in. aft of the nozzle throat plane.

A total system torque of 107,500 ft-lb was used to size the nozzle actuation system components. With a moment arm of 51.6-in., the actuation force requirement is 25,000 lbf. Two servoactuators, one located on the pitch axi and one located on the yaw axis of the motor, furnish the force to deflect the nozzle omniaxially. Each actuator has a 10-in. stroke and incorporates a mechanical feedback system for position control. Both electrical and hydraulic redundancy is incorporated in the servoactuators. A dual electric command system containing three channel input, two actual and one model, is used. In addition, each actuator has dual tandem units so that even with the complete failure of an actuating cylinder, the actuator will still operate at one half its load capacity.

To meet the system requirement of a 5 degree/sec slew rate and a duty cycle consisting of 135 degree/sec with vectoring command up to 25%

II.C. Preliminary Design (cont)

of the total motor burn time, an electro hydraulic power supply unit was selected. Hydraulic power is supplied by two completely independent units for redundancy. Each unit consists of a nickel-cadmium battery, dc motor/pump, hydraulic reservoir, and accumulator. The motor pump is sized to deliver the average power requirement of 3 gpm at 3000 psi pressure and runs continuously to charge the accumulator during periods of low demand. The accumulator is precharged during ground checkout to reduce the total demand on the battery. In the selection of the components, maximum use is made of designs and components that have been flight qualified in man-rated systems.

Components of the two power supply units are installed on the aft skirt in the quadrant between the two actuators. The two units are interconnected with the actuators so that even with the power loss of one unit, full nozzle deflection capability is available at a reduced nozzle deflection rate. The actuators are installed through end fittings to the nozzle exit cone and motor aft skirt components.

The total weight of the selected TVC actuation system is 600 lbm. The weight breakdown is as follows:

Battery (2 units)	200
Motor/Pump (2 units)	80
Servoactuator (2 units)	150
Accumulator (2 units)	56
Reservoir (2 units)	40
Lines, Fittings, Electronics	50
Hydraulic Fluid	24
Total	600 lbm

The net weight increase for the TVC system, including chamber, insulation, and the 1380 lb flexible seal, is 4,033 lbm.

II.C. Preliminary Design (cont)

Two other types of power supply systems were considered for this application. These types are a blow-down system and a warm gas generator system. In the blow-down system, hydraulic supply for the servo-actuators is contained in two large accumulators. Each accumulator is precharged and is sized to provide the fluid capacity for the total duty cycle. The hydraulic fluid is nonrecirculating. This results in a simple, reliable, and low cost system. However, for the assumed TVC requirements the cost advantage of the blow-down system over the selected motor/pump system is relatively small. In addition, the blow-down system has the disadvantages of a substantially higher weight and the hazards of high pressure accumulators. A blow-down system should continue to be considered, however, until the final analysis and selection phase when the TVC requirements are more fully defined.

In a warm gas generator system, gas from the generator is the primary power source to activate pneumatic-type actuators. The gas flow is controlled by a bi-stable flapper valve which controls the flow to the turbine wheels with opposing buckets. The turbine speed is reduced through a gear and a harmonic drive to finally drive a ball screw actuator. Although this system is very promising, its cost, reliability, and performance have no been thoroughly proven.

11. Thrust Neutralization System

For thrust neutralization, a conventional forward head venting system was selected. As shown in Figure II-36 two ports located 180 degrees apart on the forward head are opened to neutralize the motor thrust. The ports are oriented 35 degrees from the motor axis. With this orientation, the two 49.5-in.-dia vent ports provided the capability of either reversing or negating the thrust at any time during motor burn. Neglecting the weight of the motor, the reversed thrust is a maximum of 56,000 lb at start of motor burn and decreases until the reversed thrust just balances the nozzle thrust at the motor

II.C. Preliminary Design (cont)

burn time of 135 sec. Neutralization is estimated to be achieved within 4 millisec of initiation. The venting transient for a condition near the end of boost, which is the longest blow-down condition is shown in Figure II-31.

Each port is opened with a redundant system of two shaped charges. Each shaped charge is independently detonated with separate initiators.

The flow of exhaust gas through the ports is controlled by a stack that has a 15 degree half angle. The stack liner consists of a tape wrapped silica cloth phenolic throat and V-44 rubber. The steel shell of the stack is bolted to the reinforcement boss on the motor case. The exit plane of the stack is bolted to the nose cone through a V-45 rubber boot, which allows for differential movement between the forward head and nose cone during motor pressurization. An aluminum honeycomb cover provides for a continuous aerodynamic surface of the nose cone.

The system weight including structural modification of the nose fairing for two ports is 2200 lbm.

12. Performance Adjustment

In supplementing the baseline motor study, consideration was given to alternative motor sizes and characteristics. This was accomplished by calibrating a motor design synthesis computer program with the baseline design, and calculating motor characteristics over a limited range of propellant weight, MEOP, and burn time. The results are summarized in Figures II-38 and II-39, which show the effect of propellant weight and burn time on stage mass fraction and length for three values of MEOP. These data are useful in the evaluation of variations from the baseline case. No attempt was made in this study to optimize motor design characteristics.

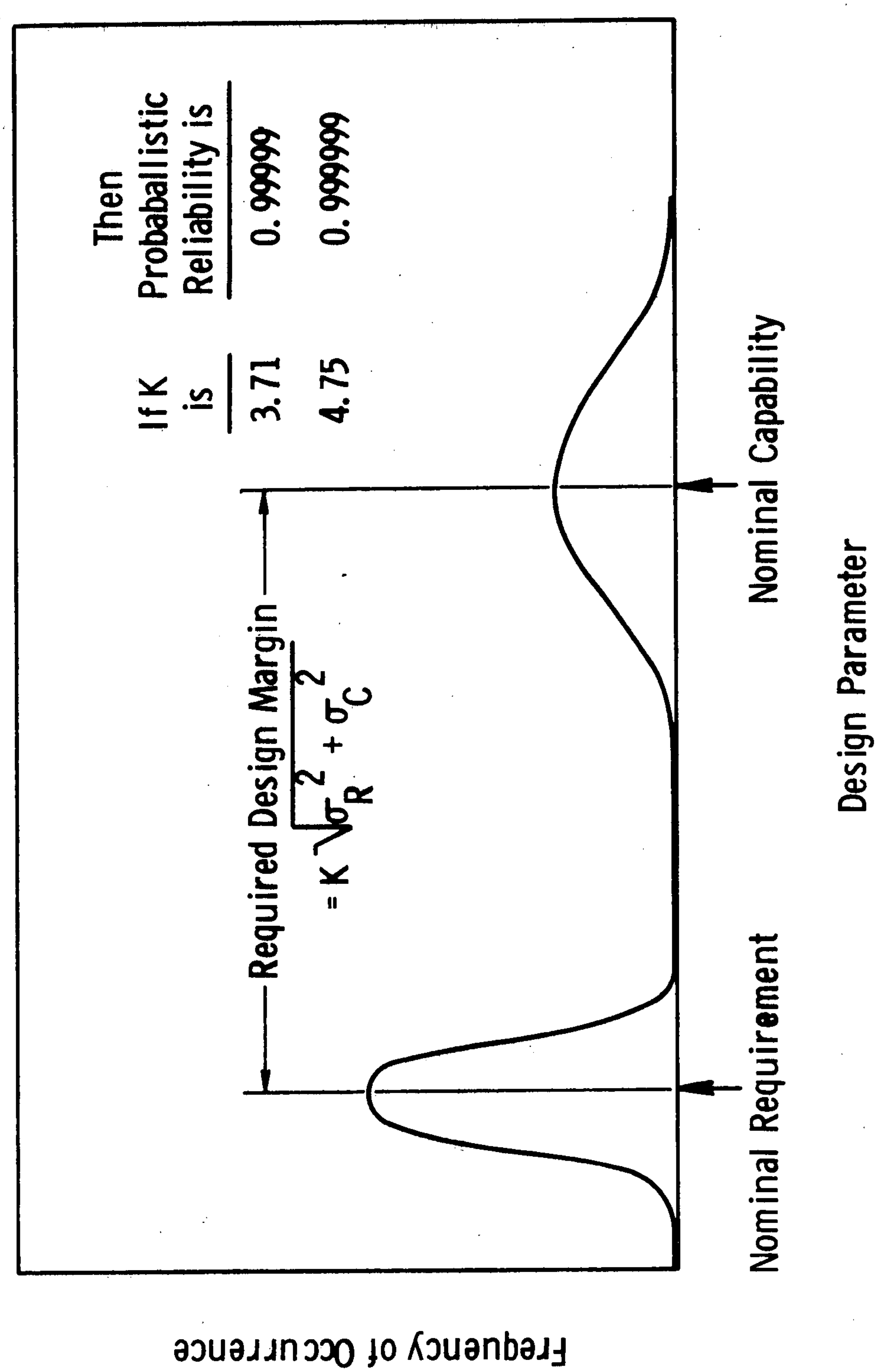
II.C. Preliminary Design (cont)

Although the baseline motor has a regressive thrust-time characteristic this type of grain is particularly amenable to adjustment to a variety of thrust schedules. A saddle characteristic has drawn some interest among the vehicle contractors for series burn applications. As shown in Figure II-40, the thrust level is allowed to regress to a low level at the 60 to 70 sec burn time range to limit the peak of dynamic pressure to 650 psf, is increased at the maximum practical rate to the nominal operating pressure, then reduced on a slope to control the vehicle acceleration to 3 g until web burnout. This type of tailoring meets the criteria for liftoff thrust-to-weight, maximum dynamic pressure, and maximum acceleration over the minimum burn time, thereby minimizing the gravity loss. The grain for this type of thrust scheduling would be hearly identical to the baseline motor grain, except the center segment ends would be restricted, the forward star grain would be slightly modified, and an additional bore taper, either in the aft segment alone or in the center segments as well, would be incorporated, with minimal effect on motor inert weight or cost.

D. SUPPORTING RESEARCH AND TECHNOLOGY

The status of large solid rocket technology has advanced to the point that no additional supporting research and technology is needed to meet the basic requirements for the SRM as they are understood. Of course, much basic design and development work remains to be accomplished in applying SRM technology to the shuttle booster. The effort has been planned as a part of the booster stage DDT&E program described in Section III of this report.

There are some areas in which technology development effort could pay dividents in reduced cost, improved performance, and improved reliability. There are others, not directly related to SRM technology, that may require supporting research and technology efforts prior to the detail design and development phase. These other areas include overall vehicle base heating effects, and SRM re-entry deceleration techniques. Further effort is needed to define specific requirements and to determine if additional research is required in these areas.



Requirement vs Capability Analysis

Figure II-1

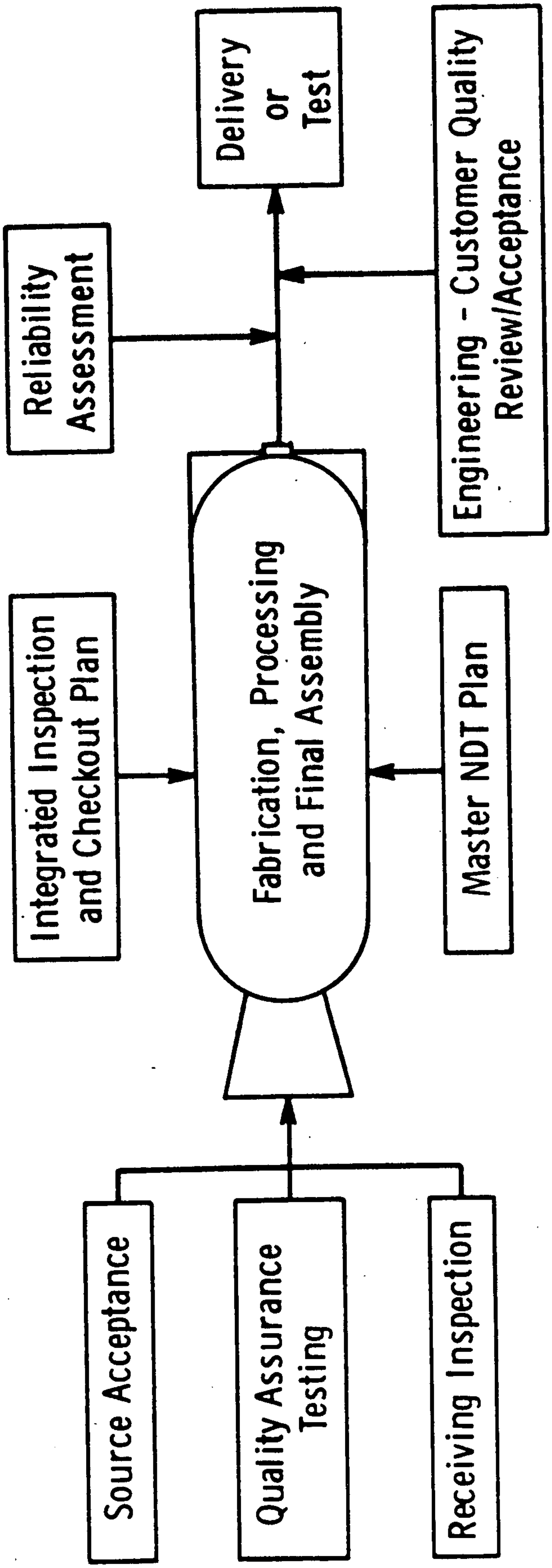


Figure II-2

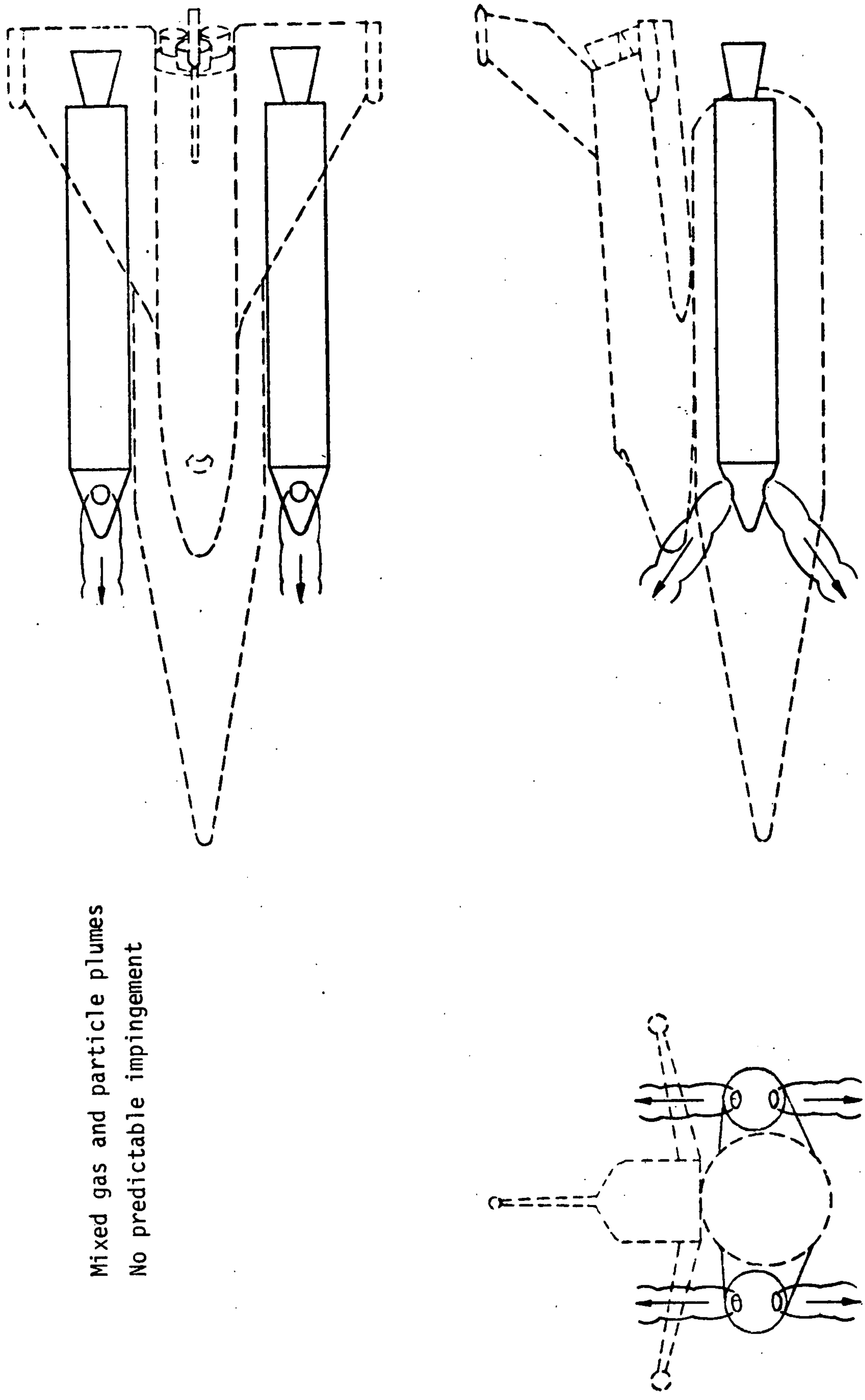
Quality Assurance Flow Plan

	Flights	Failures[1]	Production Quality Assurance Tests	Failures[1]
Minuteman I				
Stage II	231	0	64	0
Minuteman II				
Stage II	105	1[2]	42	0
Minuteman III				
Stage II	20	0	12	0
Stage III	20	0	12	0

(1) Critical failures only.
(2) Failure of TVC liquid injectant pressurization subsystem causing the missile to go off course and out of range safety limits. This led to command destruct.

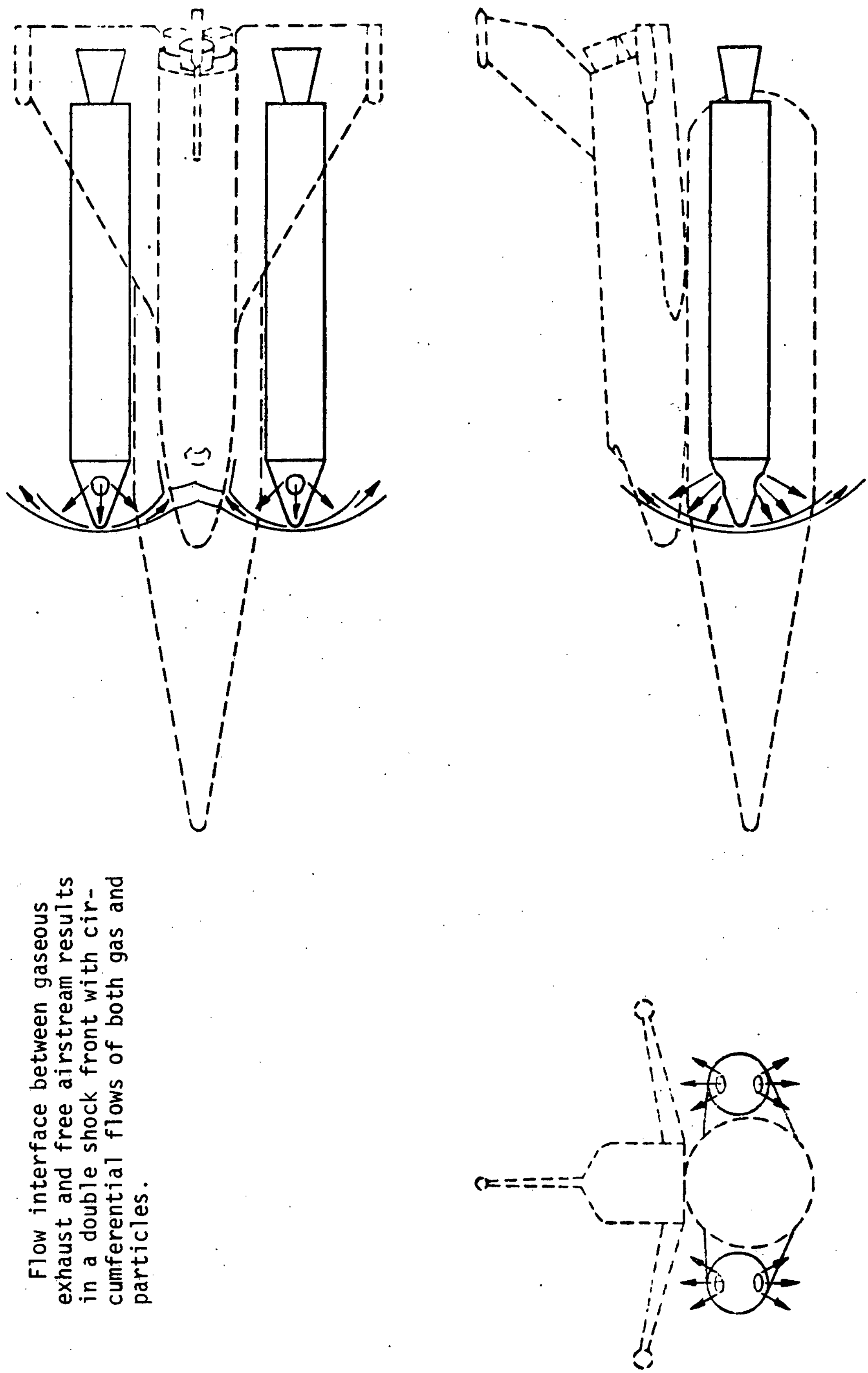
Failure Experience for Aerojet-Produced Minuteman Operational Stages

Figure II-3



Sea Level TN Exhaust Plumes

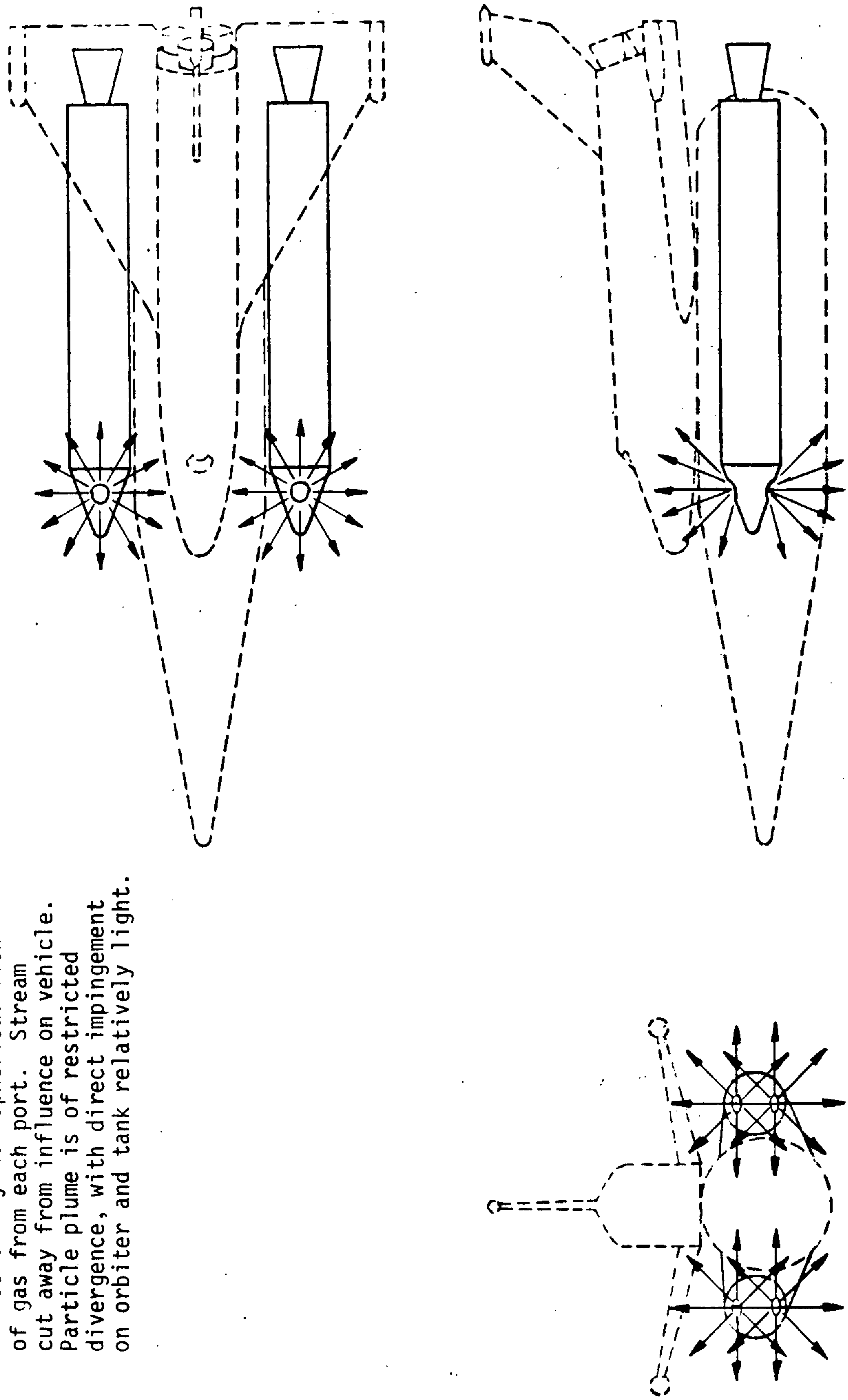
Figure II-4



Flow interface between gaseous exhaust and free airstream results in a double shock front with circumferential flows of both gas and particles.

70,000 ft TN Exhaust Plumes

Figure II-5



175,000 ft TN Exhaust Plumes

Essentially hemispherical flow of gas from each port. Stream cut away from influence on vehicle. Particle plume is of restricted divergence, with direct impingement on orbiter and tank relatively light.

Figure II-6

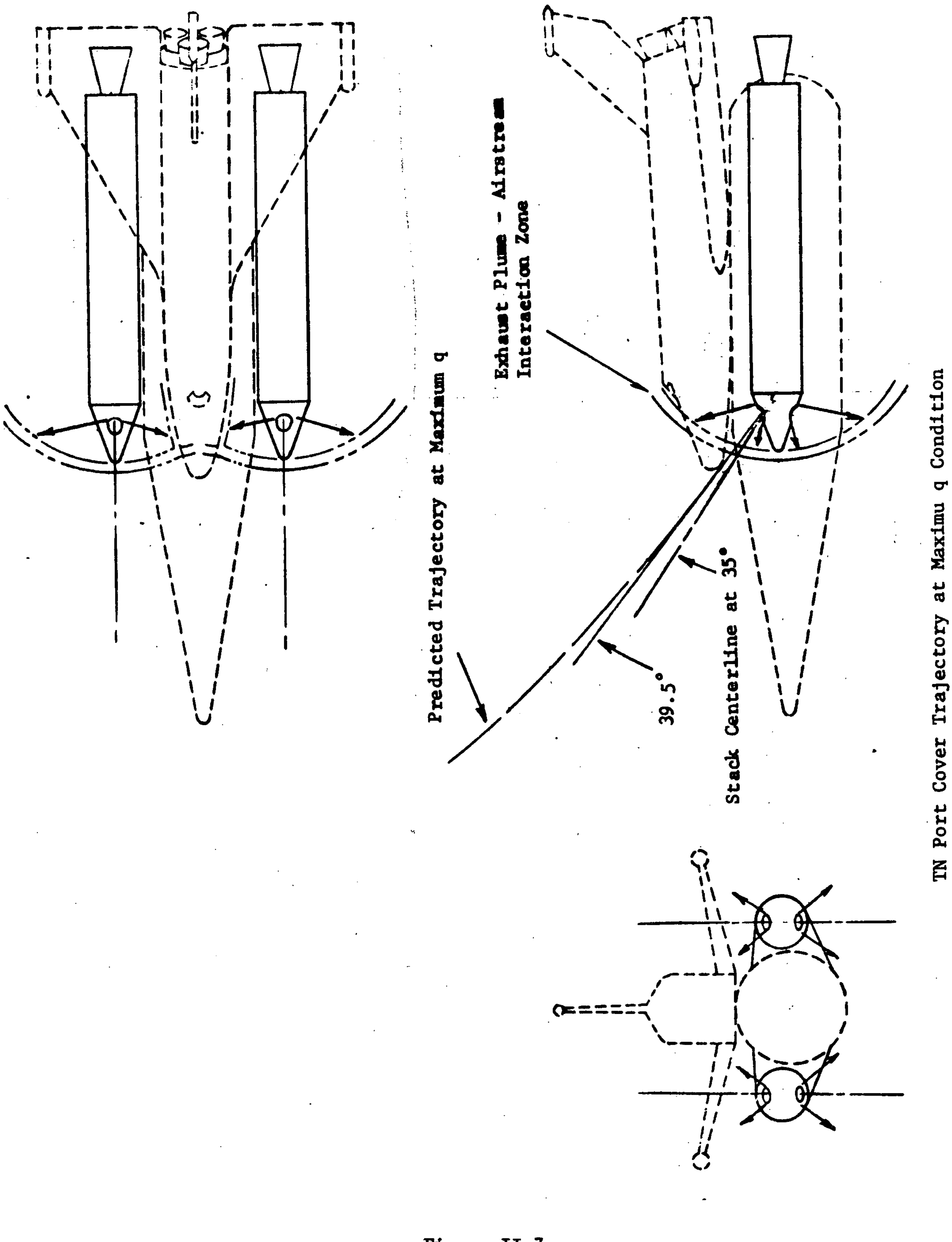
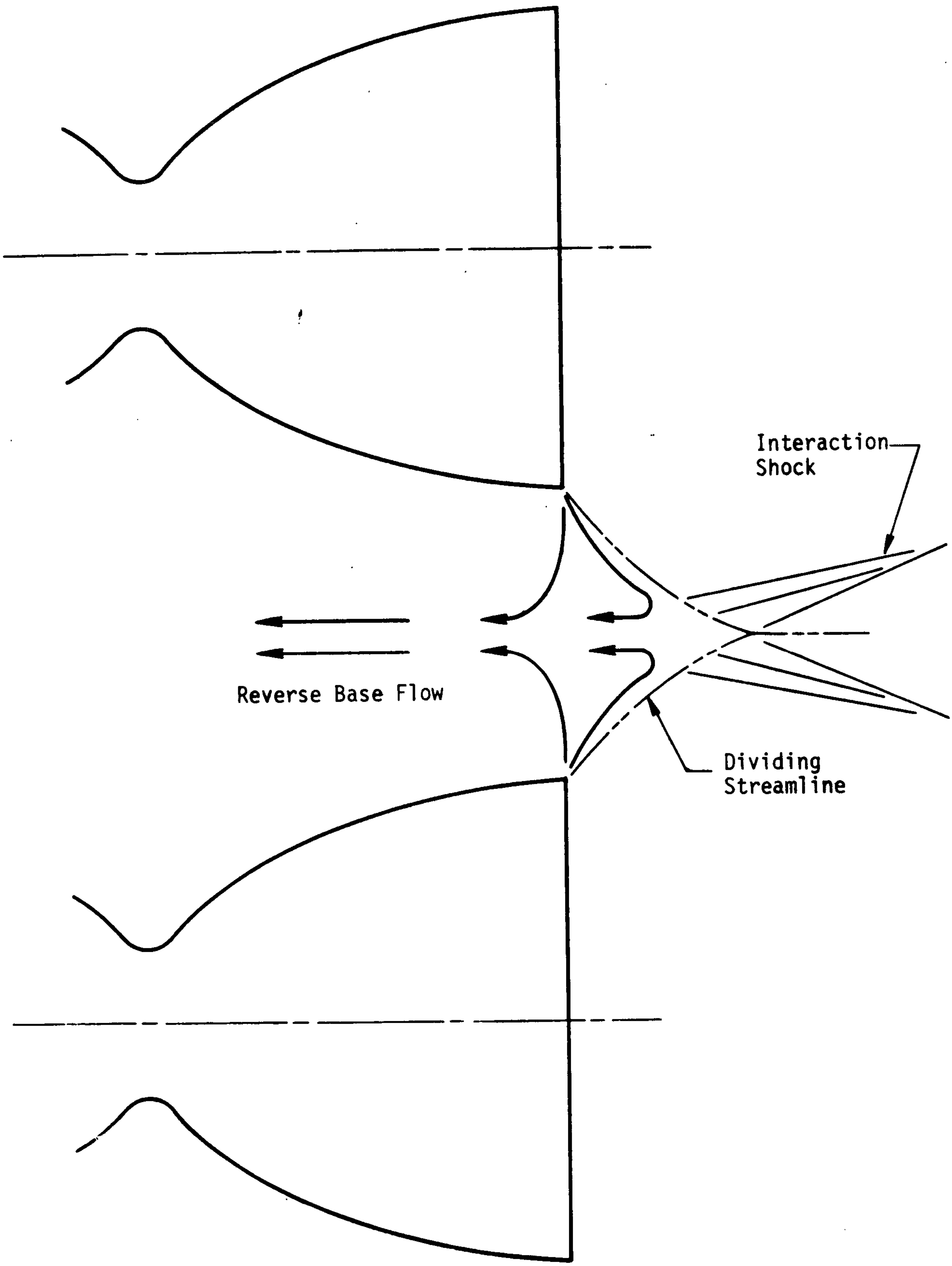
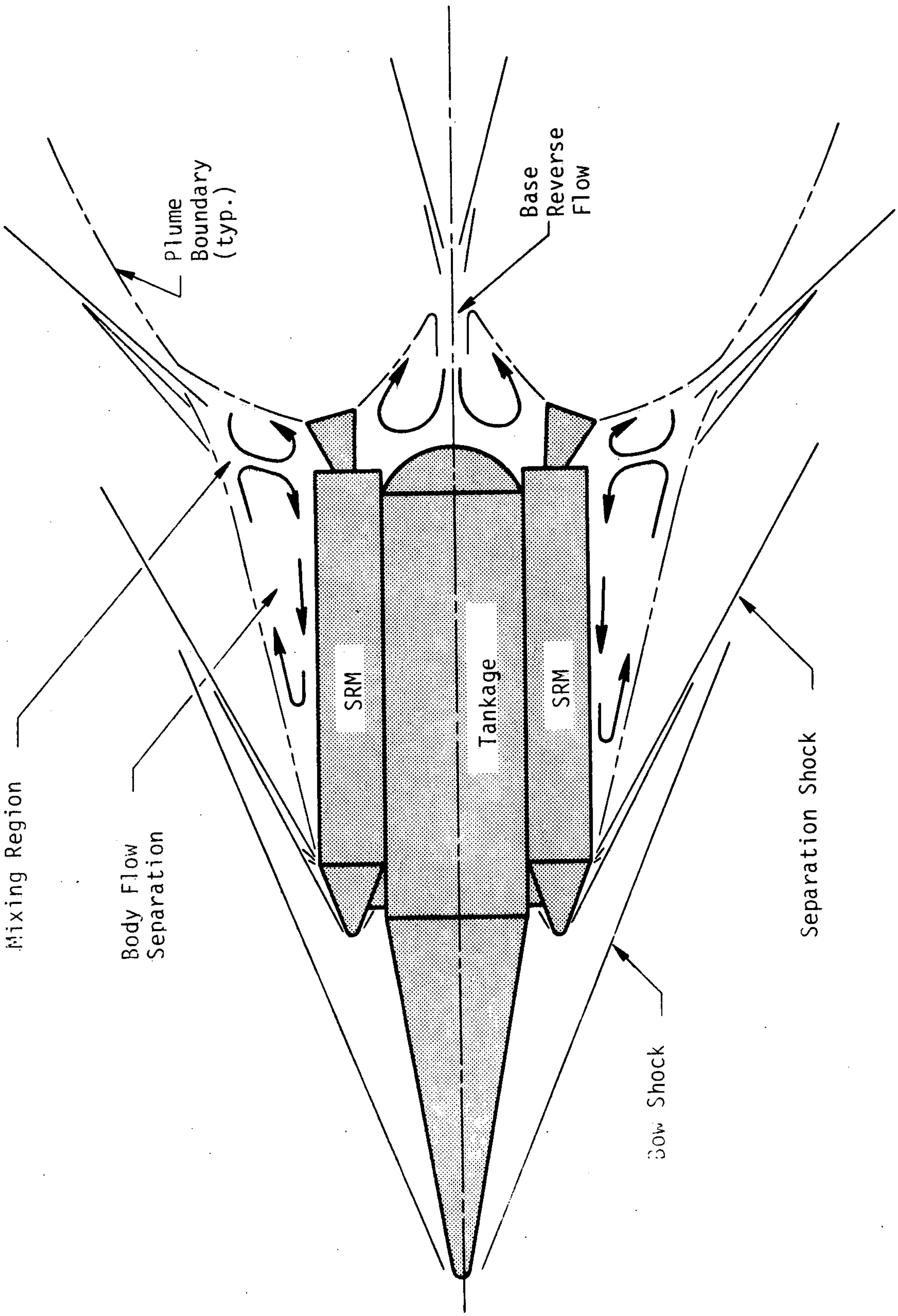

Predicted Trajectory at Maximum q
Exhaust Plume - Airstream
Interaction Zone
35°
39.5°
Stack Centerline at 35°
TN Port Cover Trajectory at Maximu q Condition

Figure II-7



Reverse Flows for a Two-Nozzle Configuration

Figure II-8



Secondary Flow in Separated Flow Regions

Figure II-9

Component	Exhaust Gas Composition Weight Percent
Al_2O_3	37.84
HCl	21.13
CO	20.52
N_2	8,21
H_2O	6,91
H_2	2,27
CO_2	2.19
H_3PO_4	0,93

Exhaust Gas Composition of Typical
Large Solid Rocket Motor

Figure II-10

	Emission, 10^6 lb/year				
	CO	NO_x	HCl	SO_2	Ash
Shuttle SRM Booster[a]	16	--	17	--	30[d]
Automobiles[b]	124,000	12,600	9[c]	--	--
Power Plants[b]	200	7,000	1340[c]	29,600	9,800
Trash Incineration[b]	15,200	1,000	400[c]	--	--
Jet Aircraft[b]	600	200	--	-	--

(a) Based on an average of 40 shuttle vehicle launches per year each using 2 SRM boosters with/million lb of propellant in each.
(b) For 1966. Source: "The Federal R&D Plan for Air-Pollution Control by Combustion-Process Modification," January 1971, PB 198-066.
(c) Estimates from Gerstle and Devitt, "Chlorine and Hydrogen Chloride Emissions and Their Control," Paper No. 71-25, Air Pollution Control Association, 1971.
(d) Al_2O_3 particles.

Comparison of Emissions into the Lower Atmosphere

Figure II-11

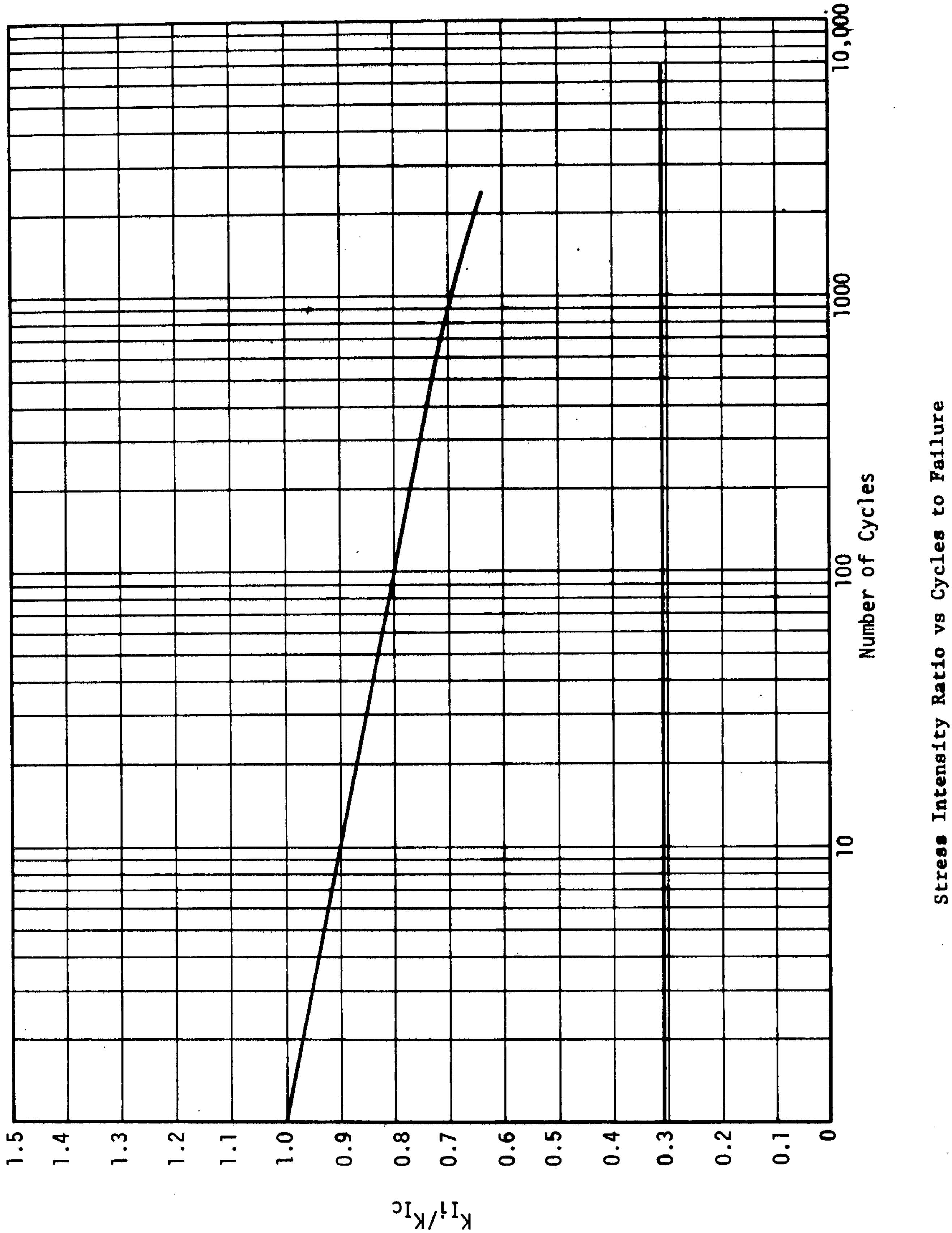
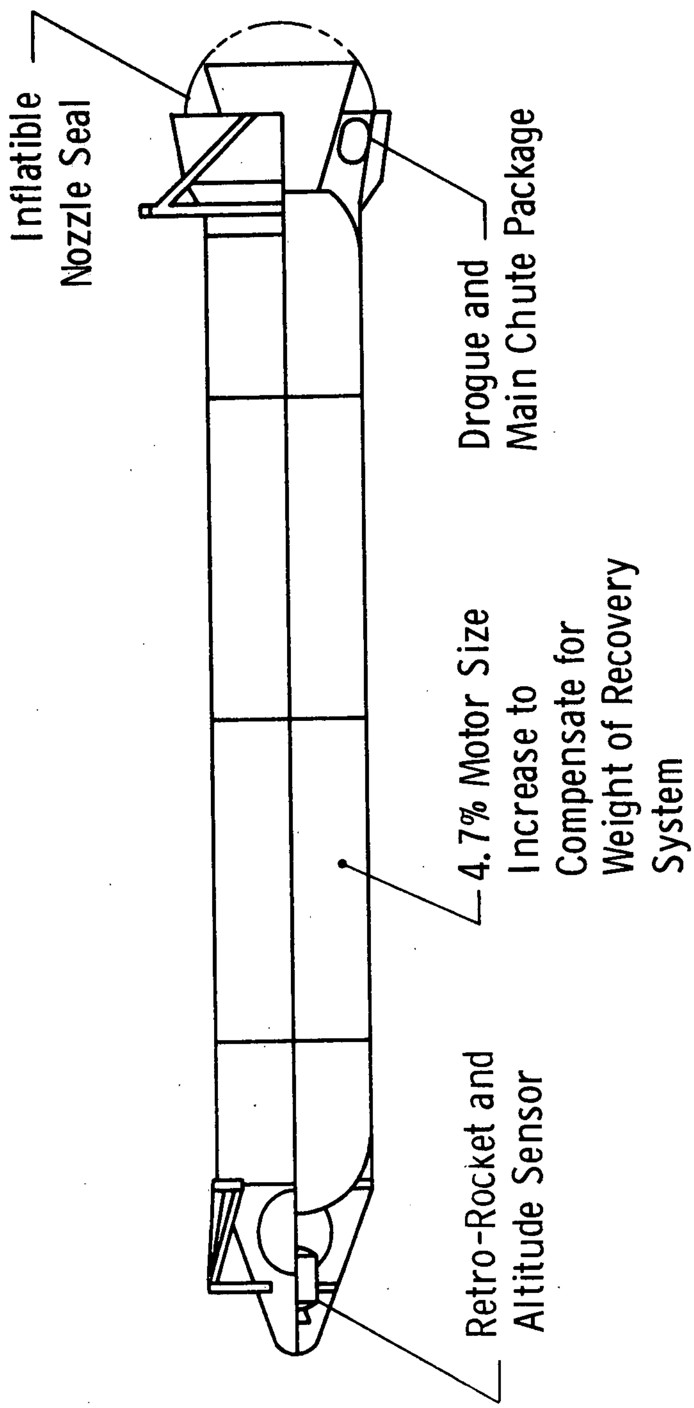

Stress Intensity Ratio vs Cycles to Failure
Number of Cycles
10
100
1000
10,000
K_{Ii}/K_{Ic}
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

Figure II-12



Recoverable SRM Booster

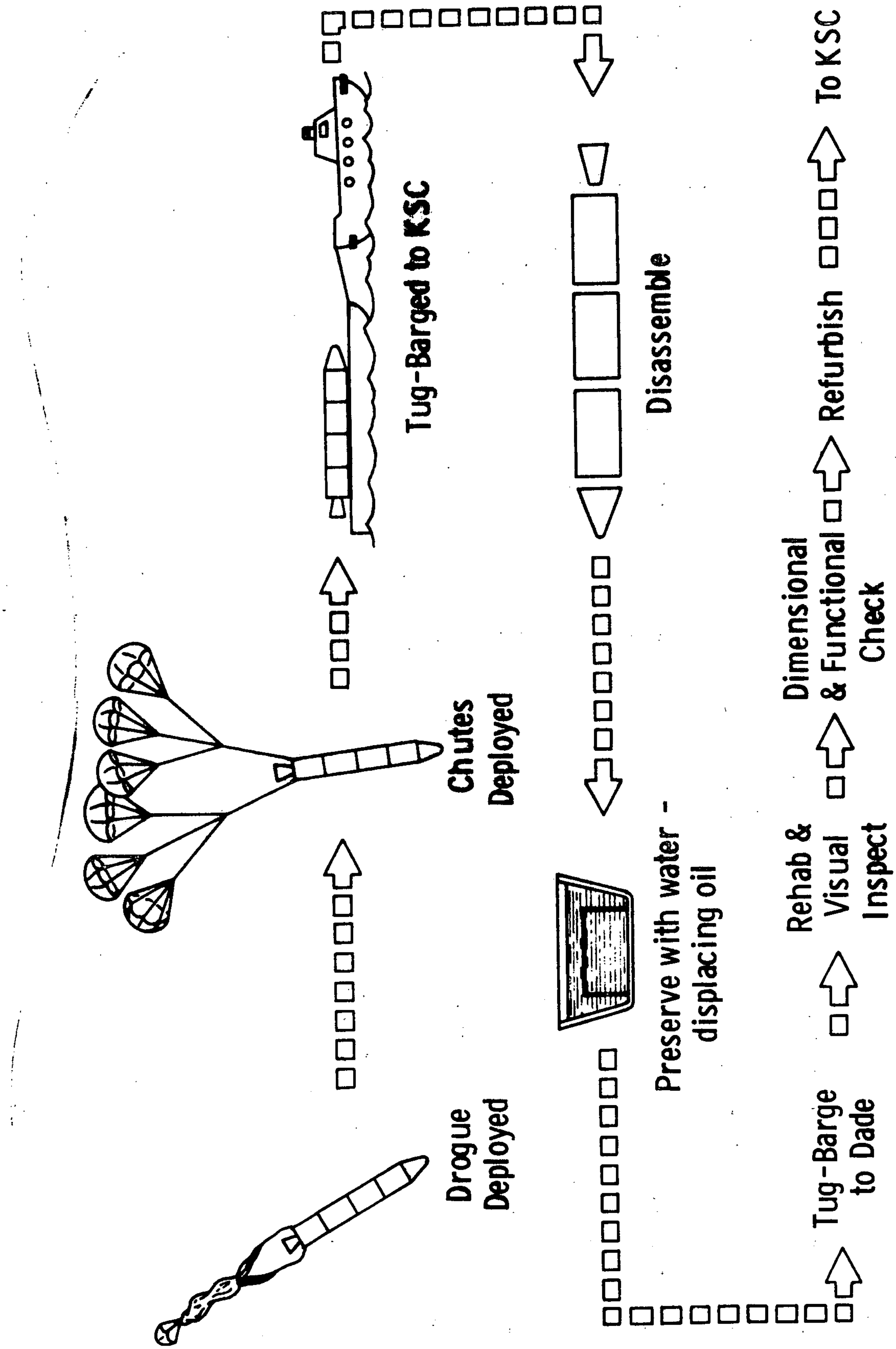
Figure II-13

	SRM Weights, lb	
	Expendable	Recoverable
Case	70,180	73,480
Propellant	1,000,000	1,047,000*
Nozzle/exit cone (no TVC)	10,860	11,370
Igniter	566	5933
Insulation/liner	14,620	15,308
Stage components	20,169	21,117
Recovery system	---	12,000
Total	1,116,395	1,180,868
Mass fraction	0.896	0.886

* To provide the same V_{stage} as the baseline.

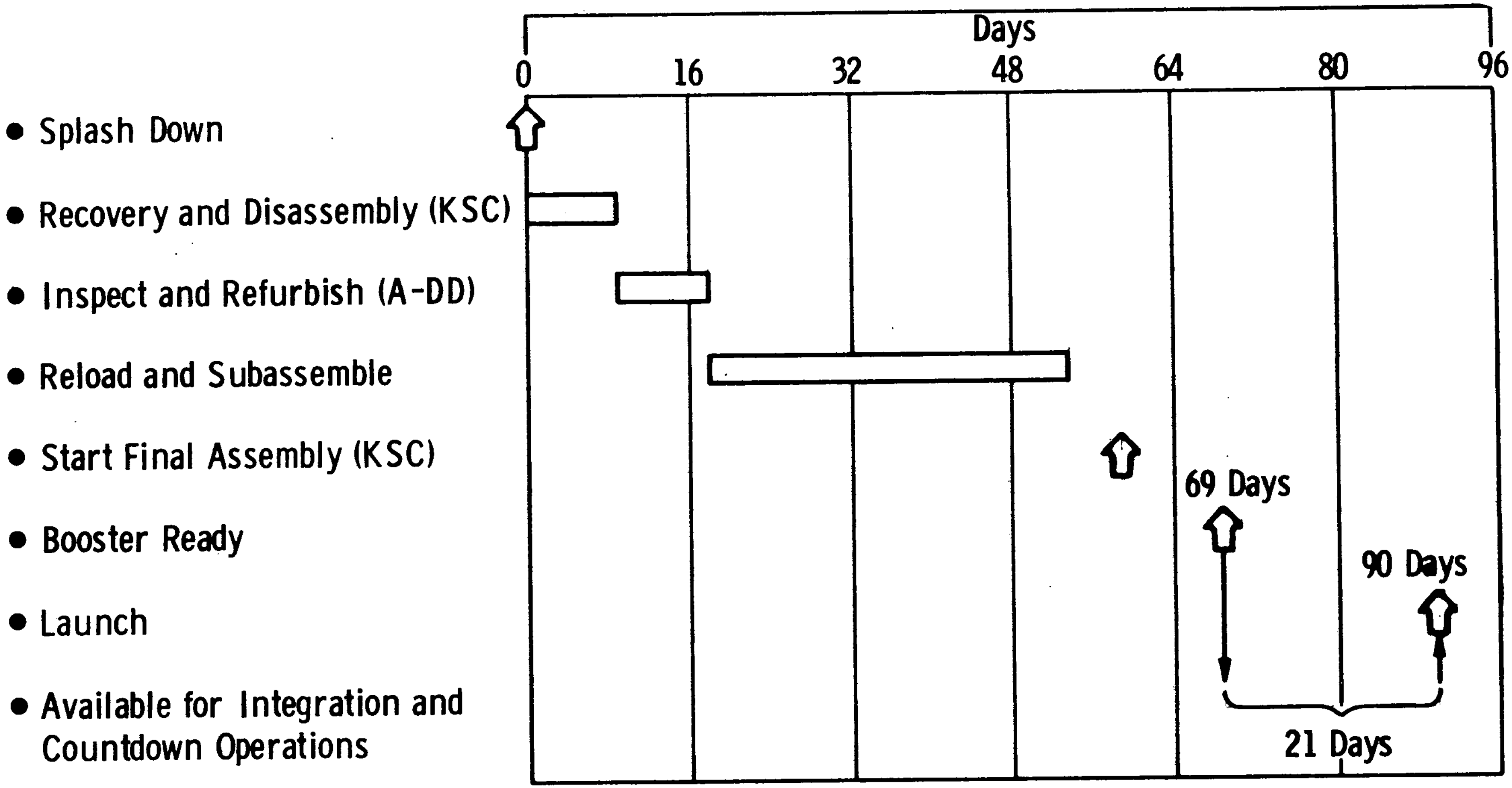
Effect of Recovery System on SRM Weight

Figure II-14



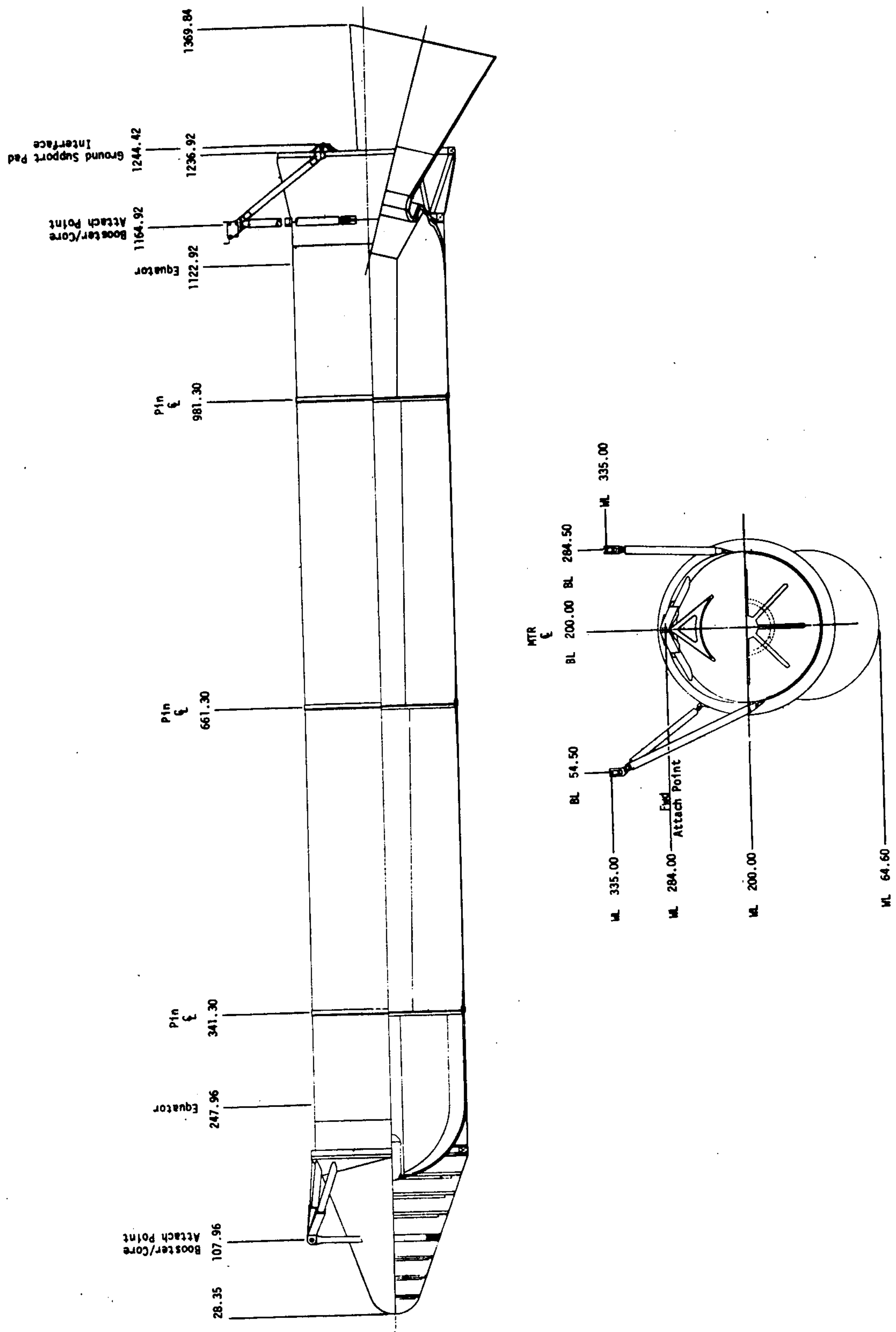
Recovery and Reuse

Figure II-15



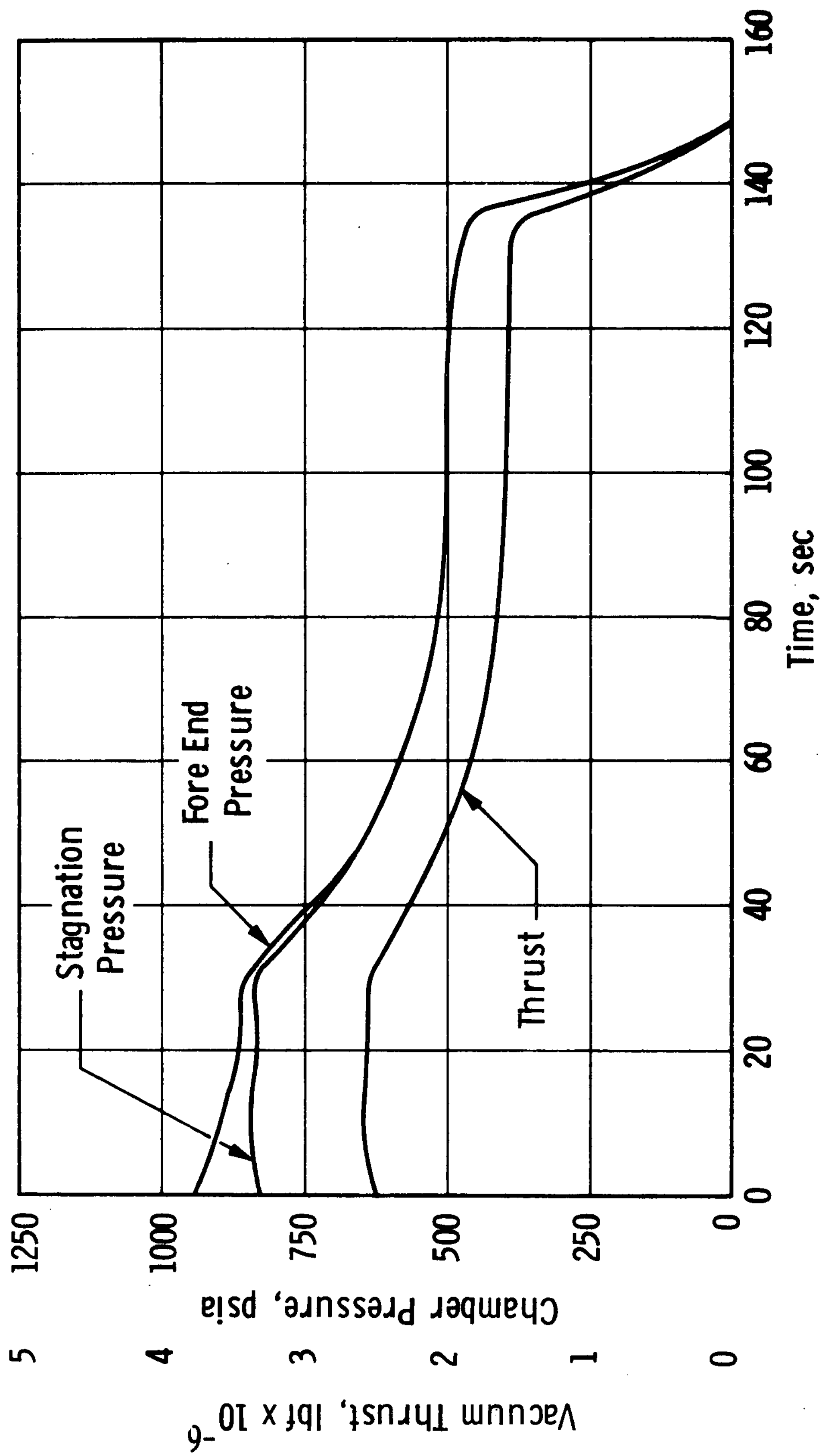
90 Day Turnaround Provides Generous Pad

Figure II-16



Baseline Motor Design

Figure II-17



Baseline Motor Ballistic Performance

Figure II-18

		$3\sigma/\bar{X}$, %
Total Impulse (vacuum), lbf-sec	271,327,000	± 0.32
Delivered Specific Impulse (vacuum), lbf-sec/lbm	271.3	± 0.12
Initial Thrust (sea level), lbf	2,244,000	
Average Thrust (vacuum, web time), lbf	1,945,000	± 1.92
Thrust Coefficient, delivered, at vacuum	1.6698	
MEOP, psia	1,000	
Maximum Nominal Pressure (70°F), psia	943	
Average Pressure (web time), psia	624	
Web Action Time, sec	135.0	± 1.92
Action Time, sec	145.0	

Baseline Motor Performance Summary

Figure II-19

MOTOR

Component	Baseline	With Thrust Neutralization and 5 Degree Thrust Vector Control
Chamber Assembly	69,030	69,600
Insulation	14,620	15,726
Nozzle Assembly	10,860	12,377
Ignition System	441	441
Subtotal	94,951	98,144
Propellant	1,000,000	1,000,000
Total Motor	1,094,961	1,098,144
Propellant Mass Fraction Fraction	0.9133	0.9106

STAGE

Component		
Nose Fairing and Forward Attach Structure	5,480	6,140
Base Support and Aft Attach Structure	9,304	9,304
Instrumentation, Destruct, and Other	800	1,040
Thrust Neutralization	-	1,540
Thrust Vector Control	-	600
Subtotal	15,584	18,624
Total Stage	1,110,535	1,116,768
Propellant Mass Fraction	0.9005	0.8954

Weight Summary

Figure II-20

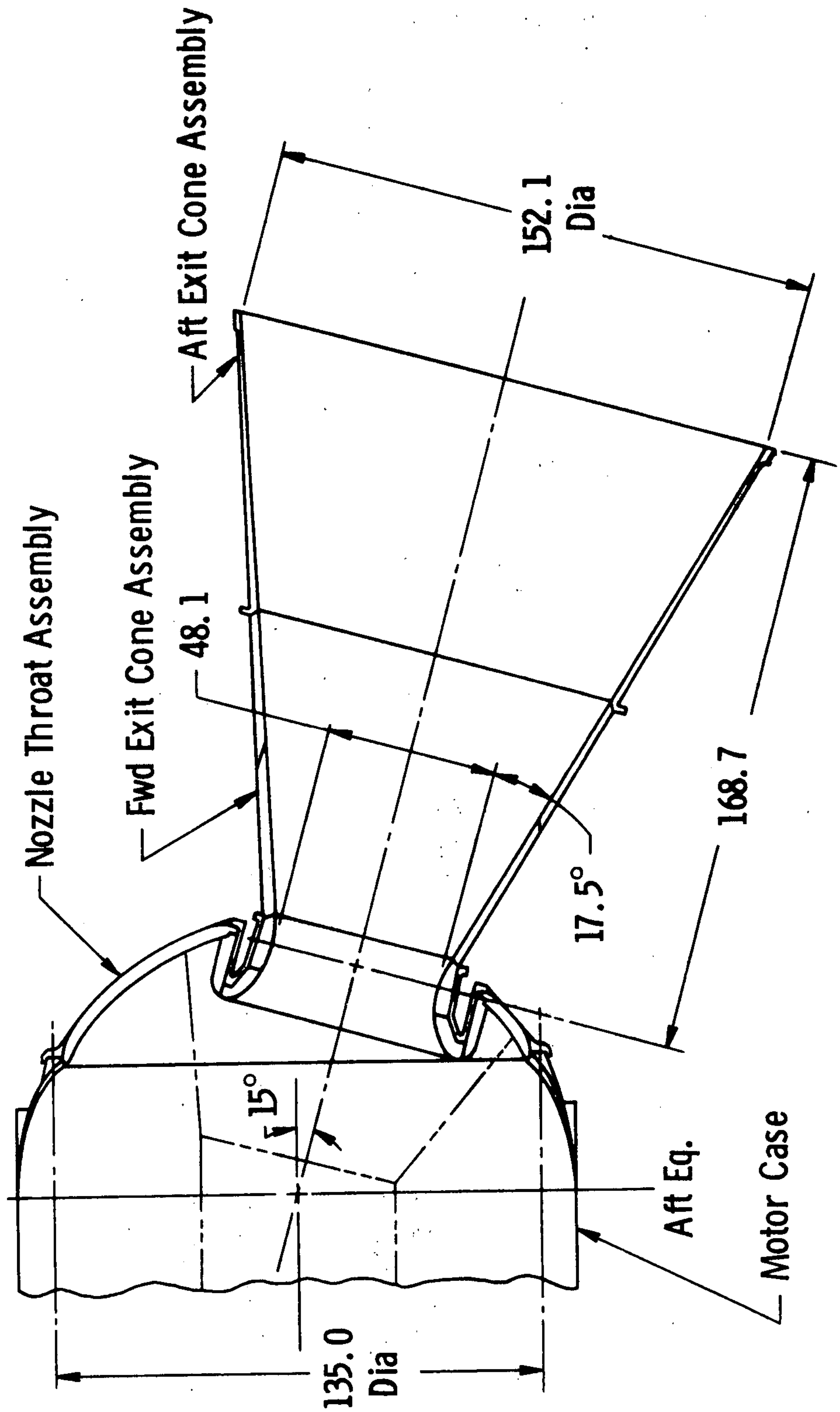
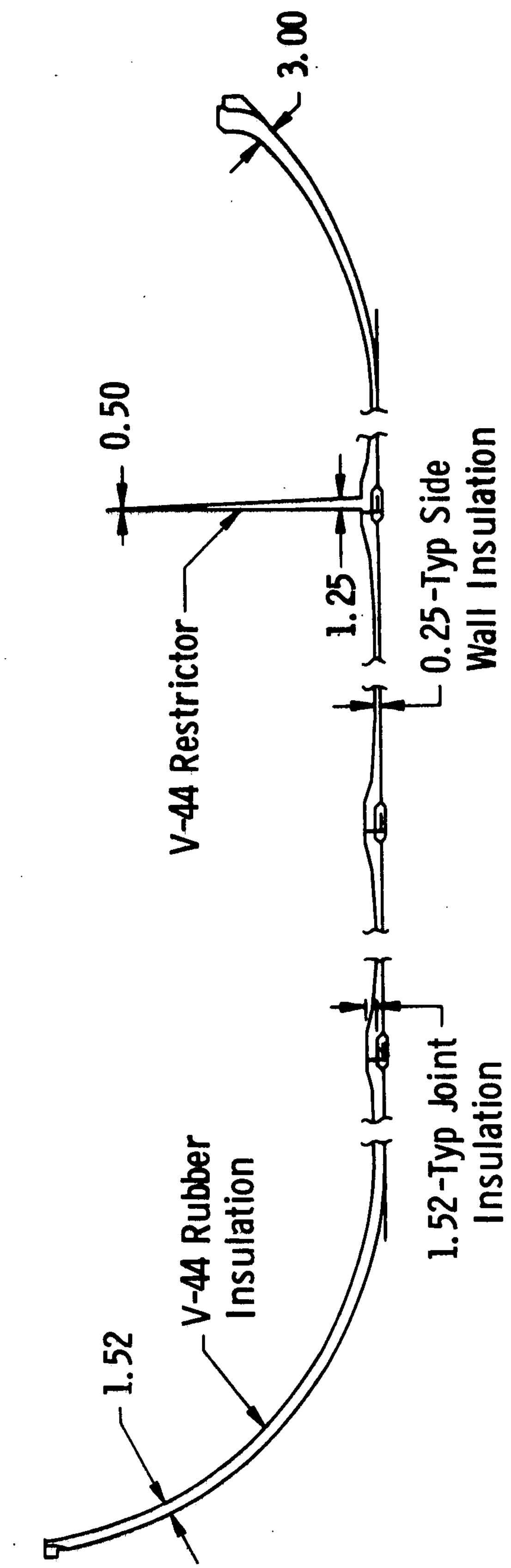


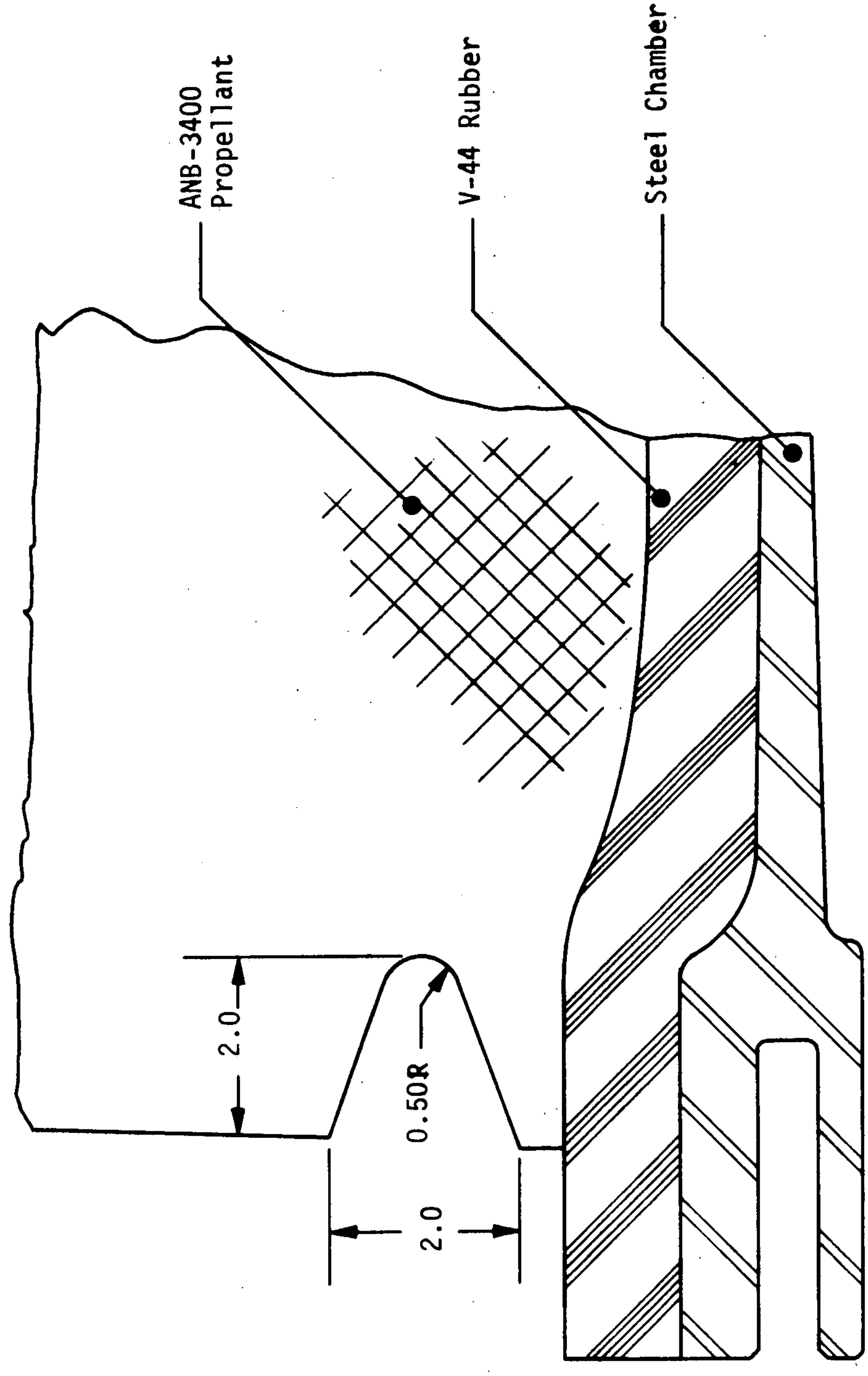
Figure II-21

Nozzle Assembly



Baseline Insulation System

Figure II-22



Detail of Bond Termination Point for 156-in.-dia Segments

Figure II-23

Condition	Bond Tension			Bond Shear			Bore Strain		
	Calc. Require. (psi)	Est. Allow. (psi)	M.S.	Calc. Require. (psi)	Est. Allow. (psi)	M.S.	Calc. Require. (%)	Est. Allow. (%)	M.S.
Storage at 40°F									
t = 6 mo									
T_{cure} = 75°F	12.0 Th.			4.0 Th.					
$\alpha_p = 5.7 \times 10^{-5}$ °F^{-1}	6.0 Acc.	22.0	4.23	2.4 Acc.	17.6	1.75	4.5	13.7	2.04
E_p = 100 psi	-14.7 Pr.			6.4 Tot.					
Acc. = 1 g	4.2 Tot.								
Firing at 60°F									
P_c = 1000 psi				2.9 Th.			3.3 Th.		
E_p = 800 psi	Compression			4.8 Acc.	400	Large	2.9 Pr.	17.7	1.85
				14.5 Pr.			6.2 Tot.		
Acc. = 2 g's				22.2 Tot.					

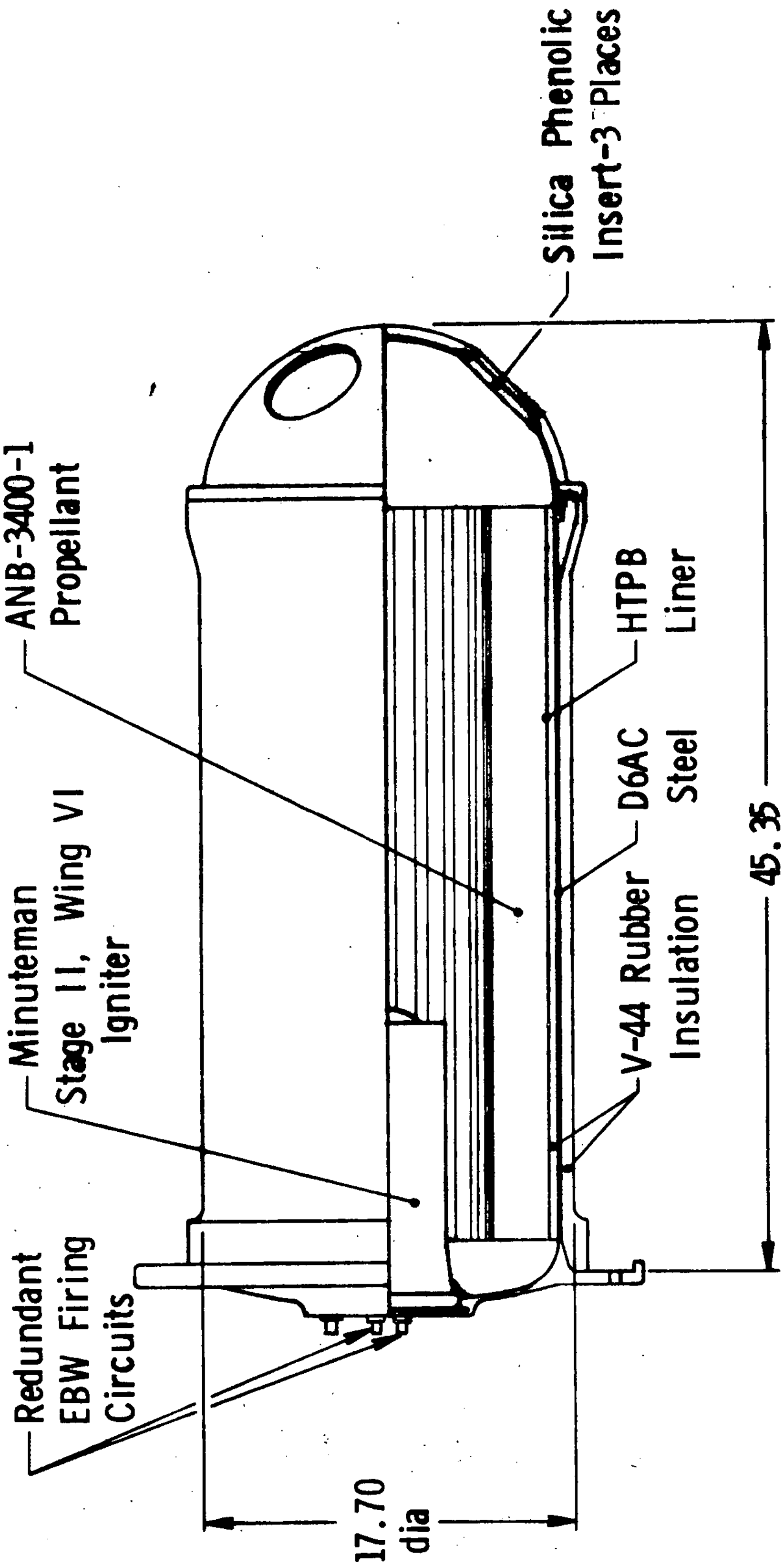
Th. = Thermal

Acc. = Acceleration

Pr. = Pressure

Summary of Structural Requirements for 156-in.-dia Propellant Grain

Figure II-24

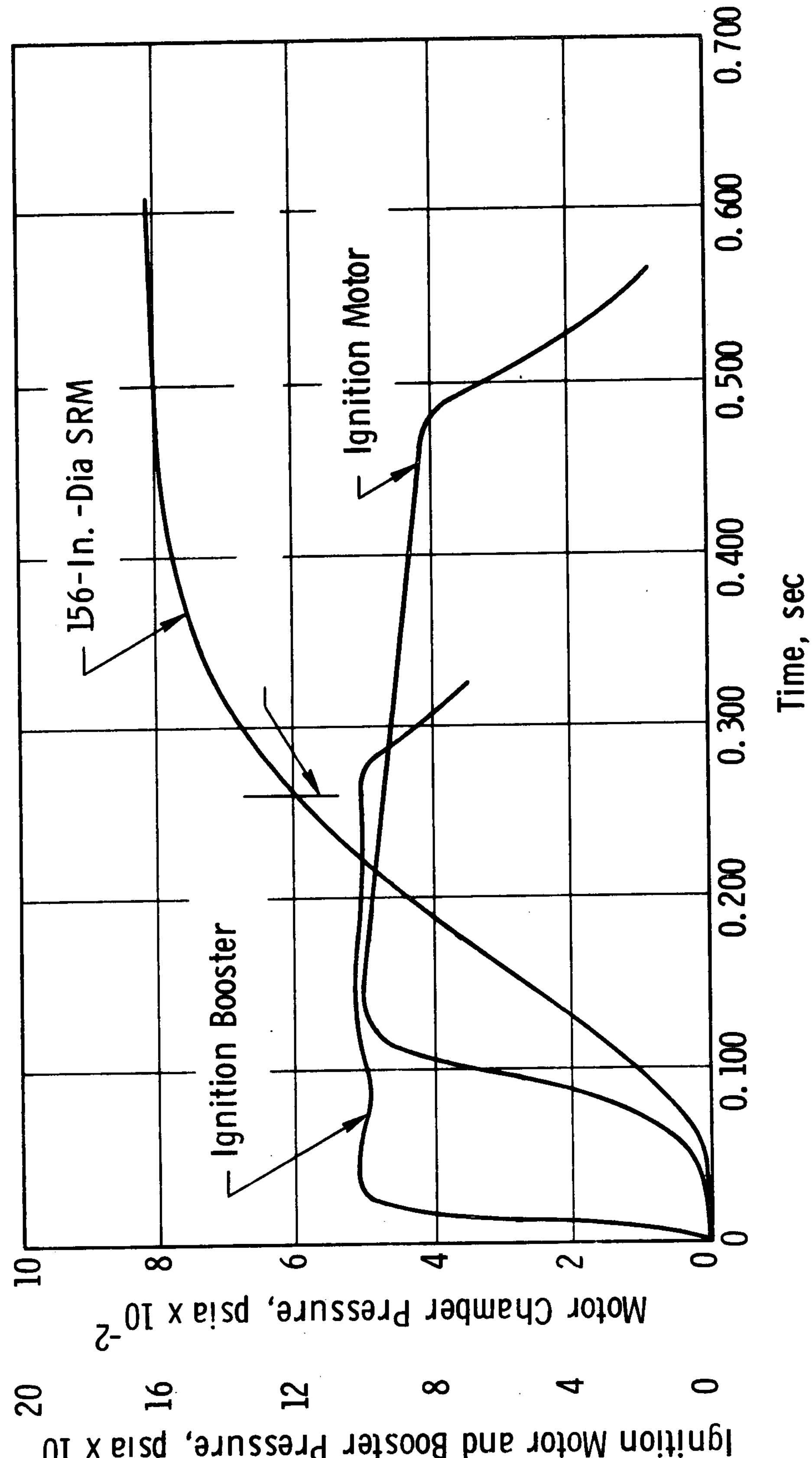


Baseline Ignition System

Figure II-25

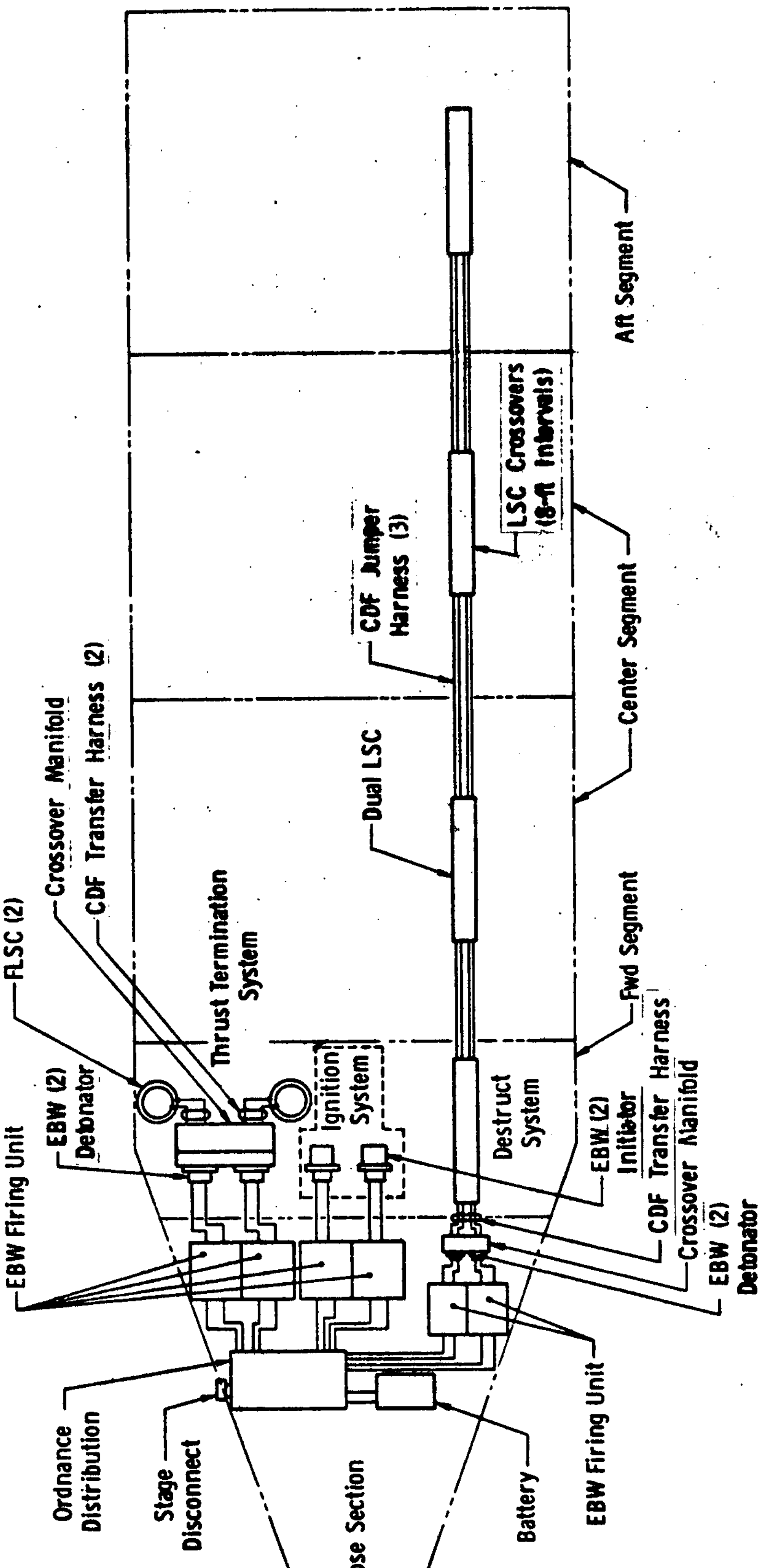
Parameters	Ignition Motor	Ignition Motor Booster	Booster Initiator
Mass Flow Rate, lb/sec	250	10.0	--
Propellant/Pyrotechnic	ANB-3400-1	ANB-3066	2D-BPN Pellets
Induced Bore Pressure, psia	22	40	N/A
Induced Heat Flux, Btu/ft^2-sec	362	400	N/A
Total Available Energy, Btu/ft^2	80	110	
Pressure:			
Operating, psia	1000	1000	1000
MEOP, psia	1250	1500	1500
Proof, psia	1875	2000	2000
Throat (Exhaust) Area, $in.^2$	40.4	1.33	0.570
Burning Surface Area, $in.^2$	5000	350	N/A
Propellant Grain Length, in.	35.0	10.2	N/A
Propellant Grain OD, in.	16.20	4.25	N/A
Burning Duration, sec	0.40	0.30	N/A
Port-to-Throat Area Ratio	3.6	3.9	N/A
Propellant (Pyrotechnic) Weight, lb (gm)	153	3.3	(37)
Thrust:			
Operating, lbf	33,940	N/A	N/A
MEOP, lbf	42,500	N/A	N/A

Ignition System Data Summary



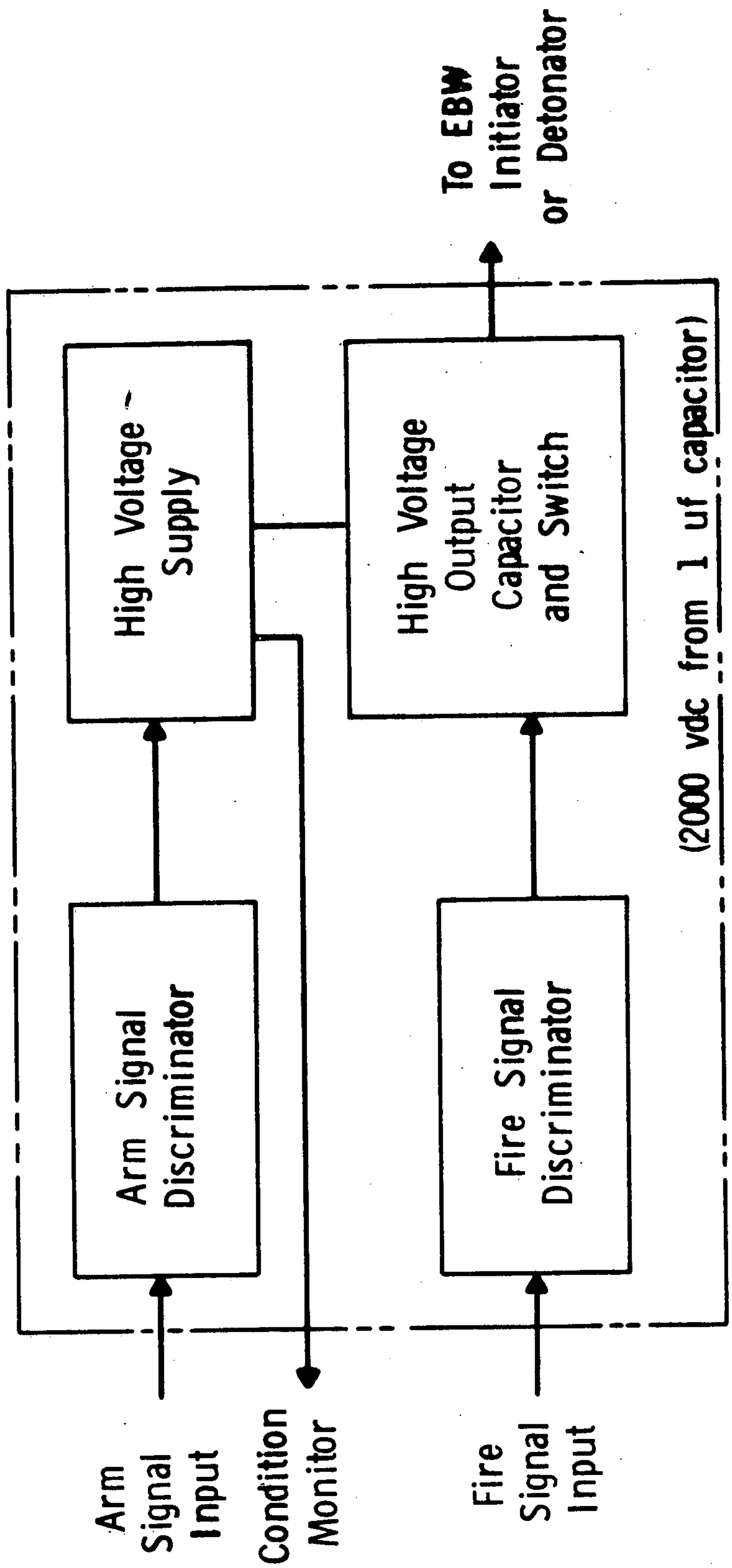
Ignition Transient

Figure II-27



Ordnance Distribution Concept

Figure II-28



Typical EBW Firing Unit

Figure II-29

EBW Initiator/Detonator

Ordnance Battery Power Monitor
Ignition EBW Firing Unit Arm Signal
Ignition EBW Firing Unit Status Monitor
Ignition EBW Firing Unit Free Signal
TN EBW Firing Unit Arm Signal
TN EBW Firing Unit Status Monitor
TN EBW Firing Unit Fire Signal
CD EBW Firing Unit Arm Signal
CD EBW Firing Unit Status Monitor
CD EBW Firing Unit Fire Signal
CD Enable/Disable Signal
Inadvertent Stage Separation Detector

Safety- and Arming-Device

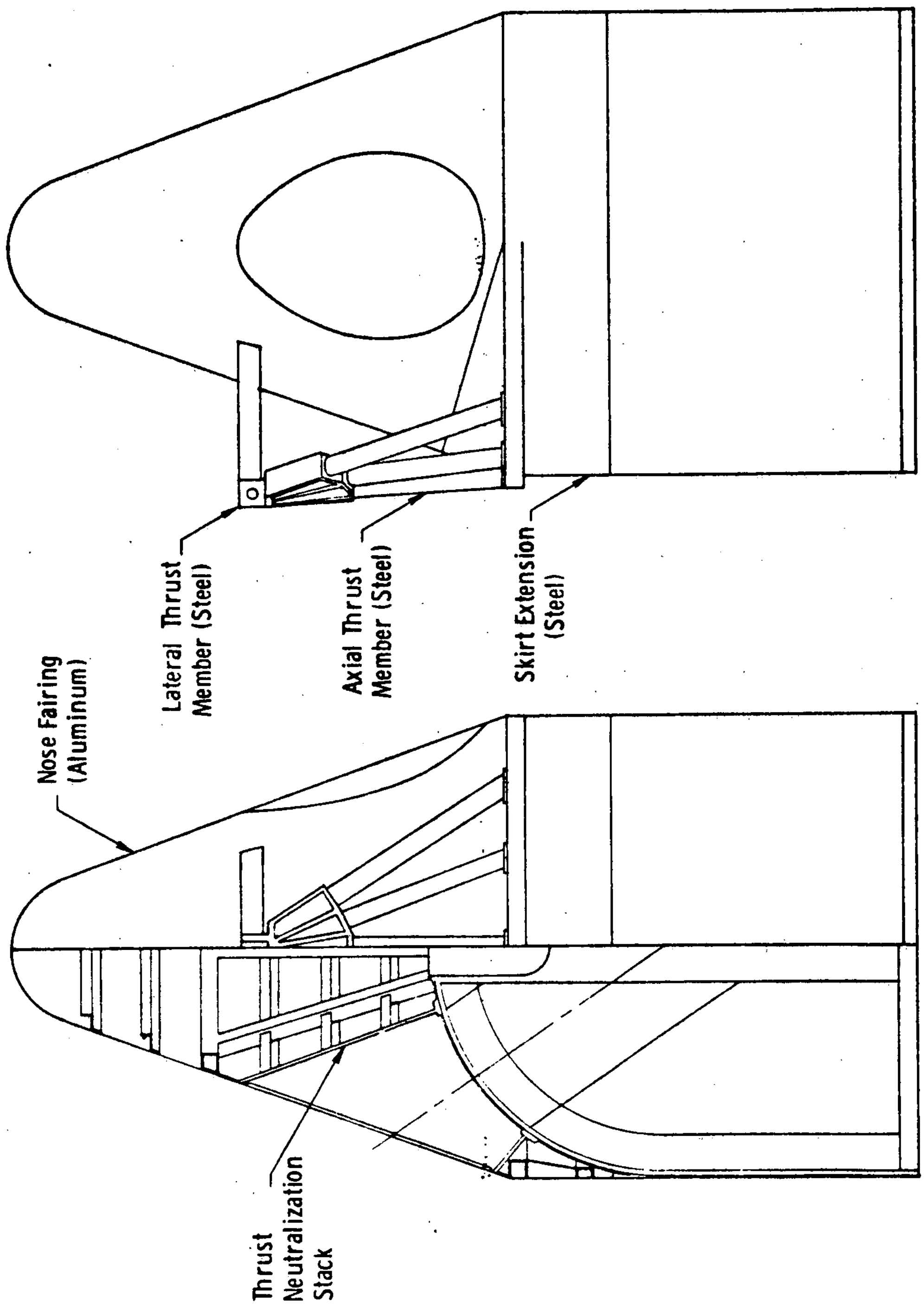
Ordnance Battery Power Monitor

Ignition S/A	-	Arm Command Signal
	-	Safe Command Signal
	-	Position Monitor
	-	Fire Signal
TN S/A	-	Arm Command Signal
	-	Safe Command Signal
	-	Position Monitor
	-	Fire Signal
CD S/A	-	Arm Command Signal
	-	Safe Command Signal
	-	Position Monitor
	-	Fire Signal
CD	-	Enable/Disable Signal

Inadvertent Stage Separation Detector

SRM-Orbiter Stage Disconnect Ordnance Signal Summary

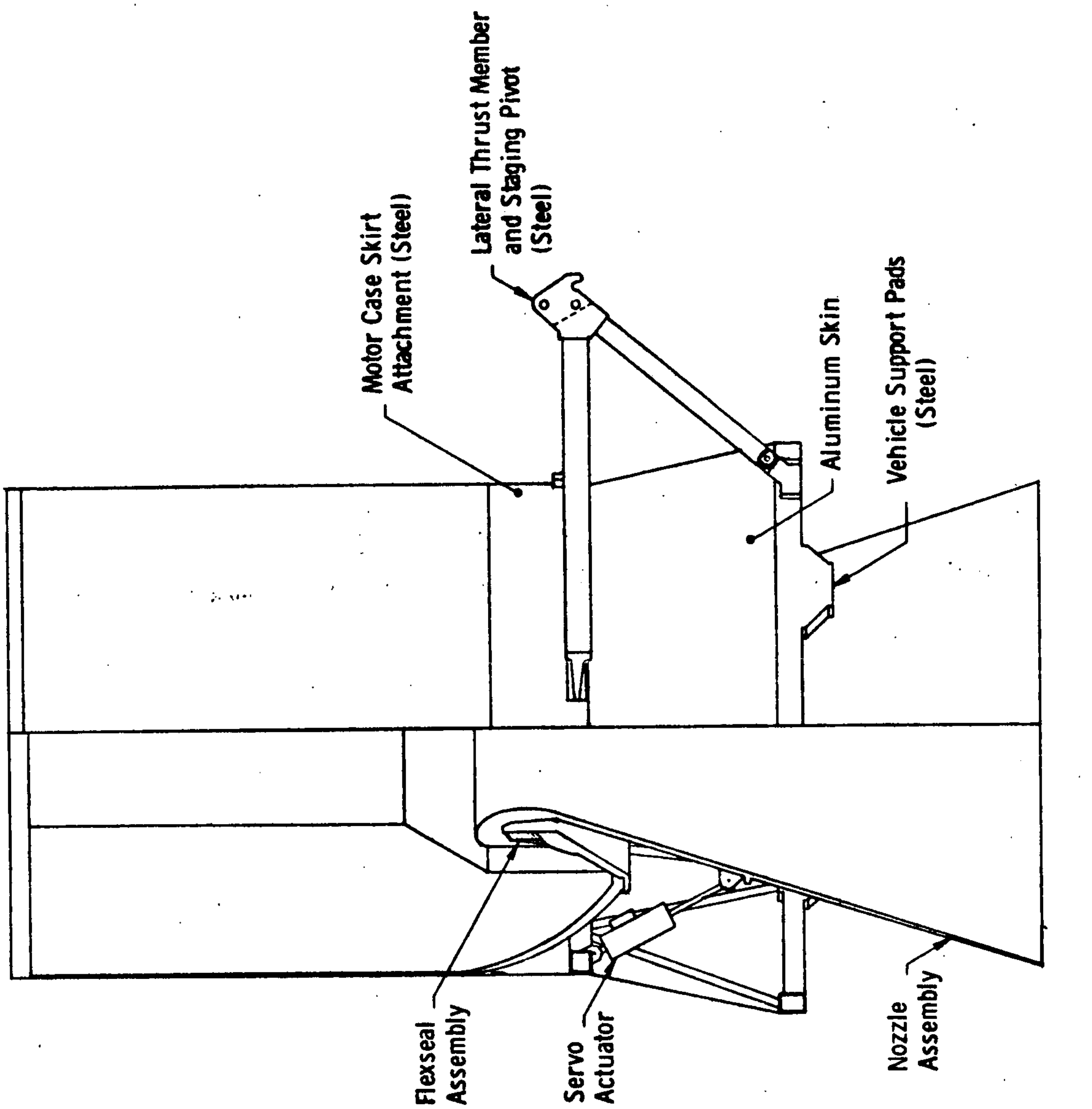
Figure II-30



Nose Fairing and Forward Attach Structure

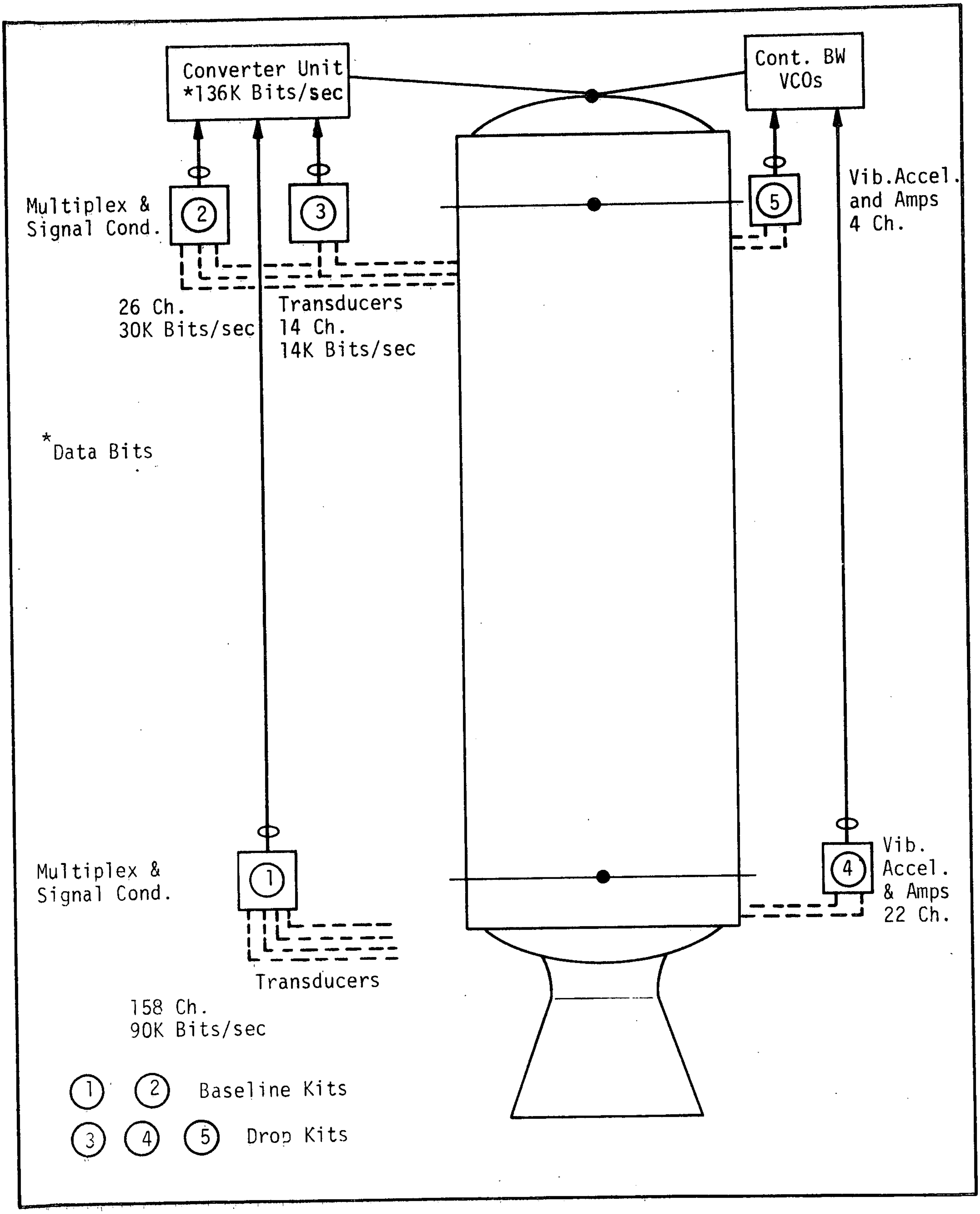
C3

Figure II-31



Vehicle Support and Aft Attach Structure

Figure II-32



SRM Data Acquisition System

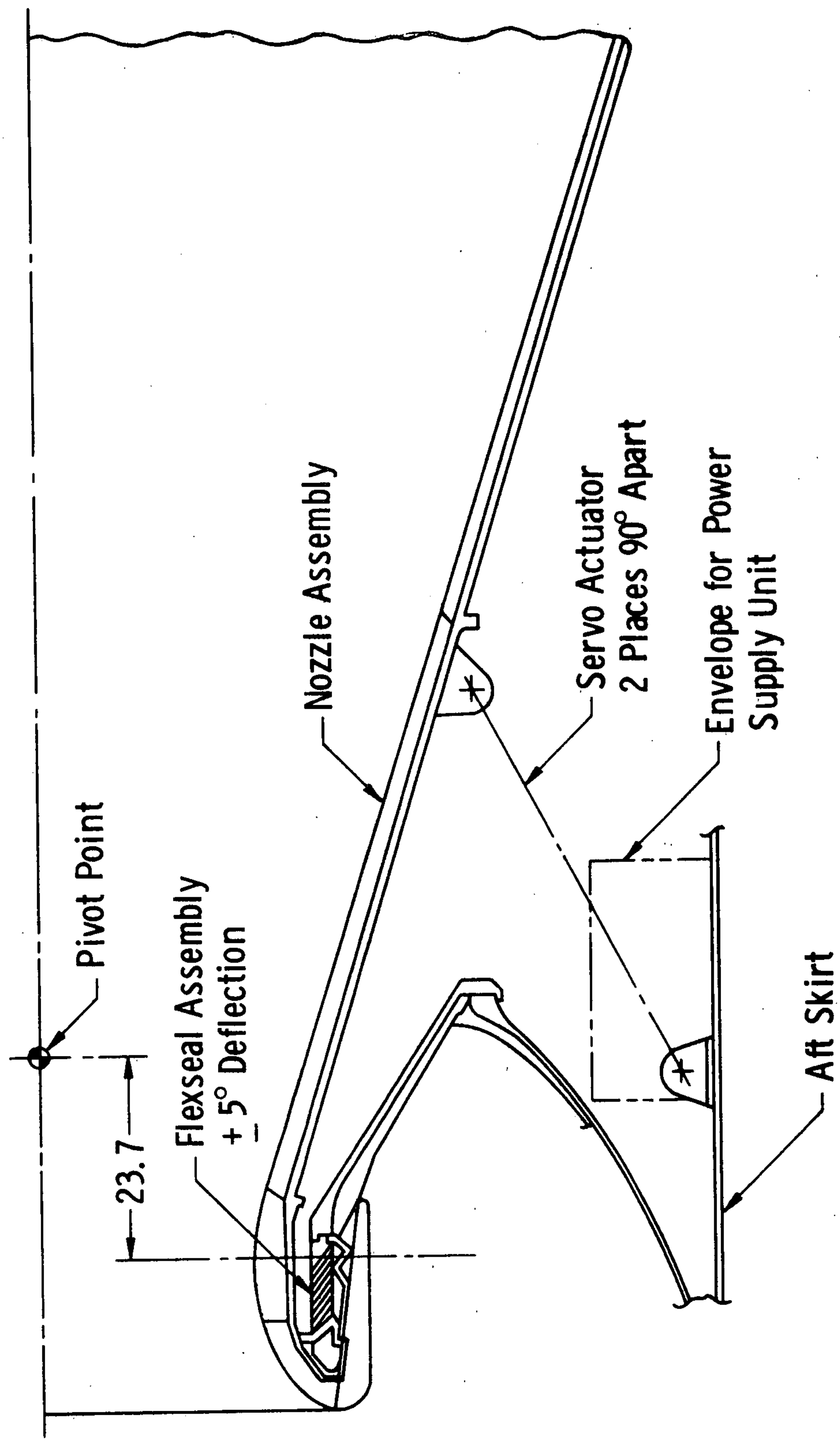
Figure II-33

Measurement	No. Channels Aft	Fwd	Sample Rate
1. Baseline			
a. Pressure:			
Motor	-	3*	400
TCV	12		100
b. Temperature (Thermocouple)	10	10	20
c. LIN. Position	8	-	100
d. Current	10	6	20
e. Voltage, Analog	20	5 (2)*	20
f. Voltage, Bilevel	20	10 (4)*	40
2. "Drop" Measurements			
a. Temperature	30		20
b. Strain	16	4	40
c. Vibration (0-2 khz)	20	4	Analog
d. Acoustics	2		Analog

* No TVC System Requirements

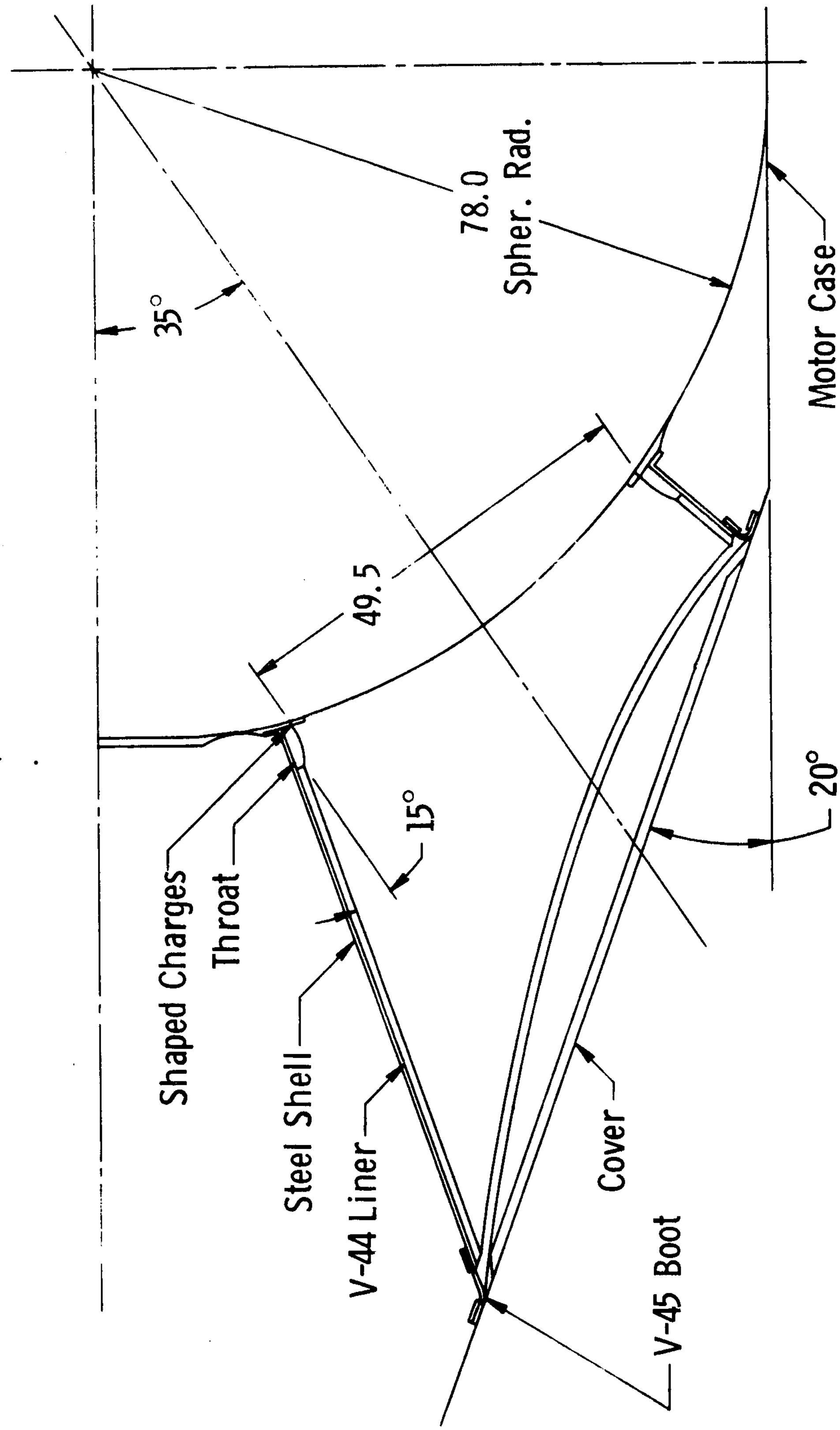
SRM Instrumentation Requirements (with TVC)

Figure II-34



Movable Nozzle TVC System

Figure II-35



Thrust Neutralization System

Figure II-36

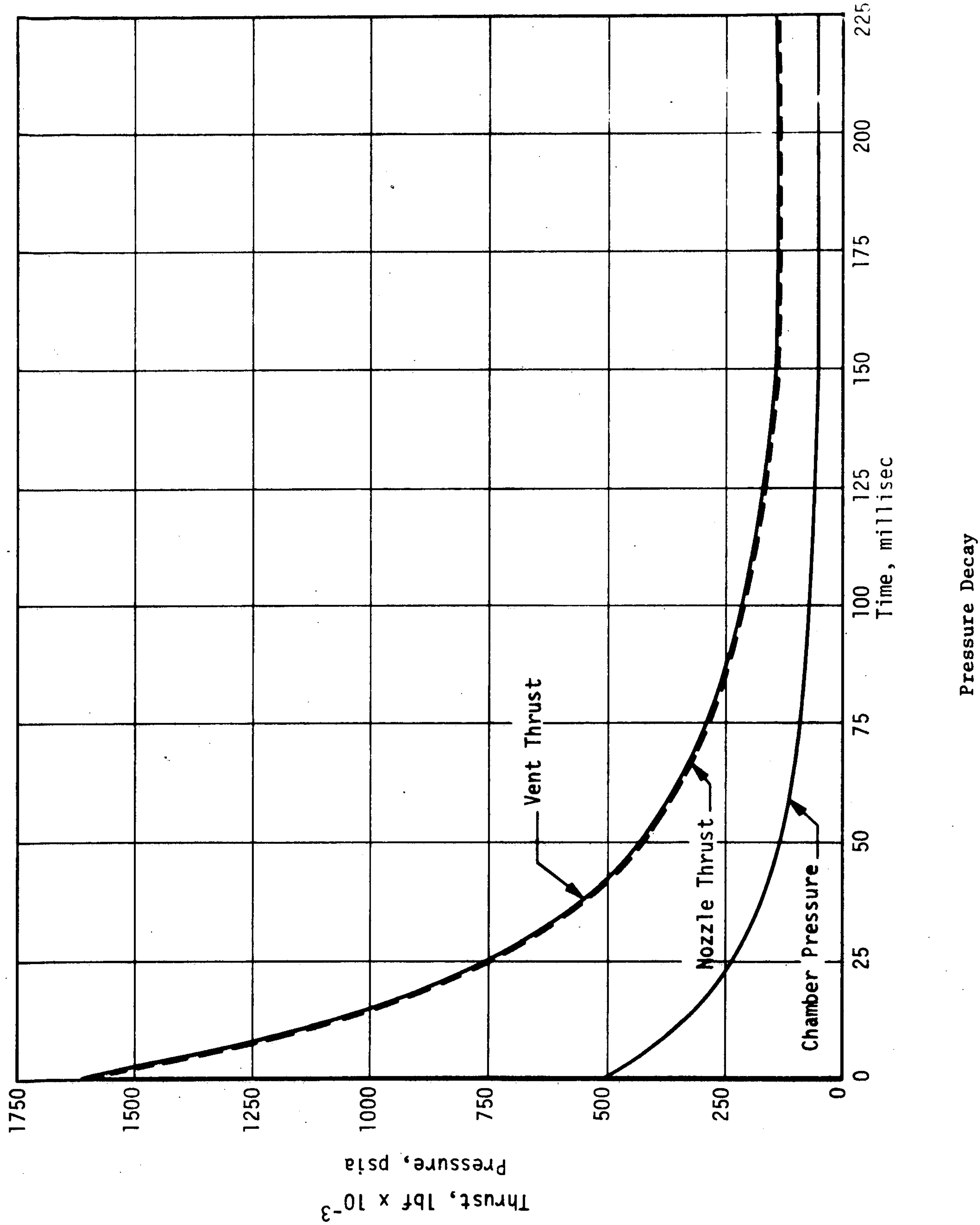
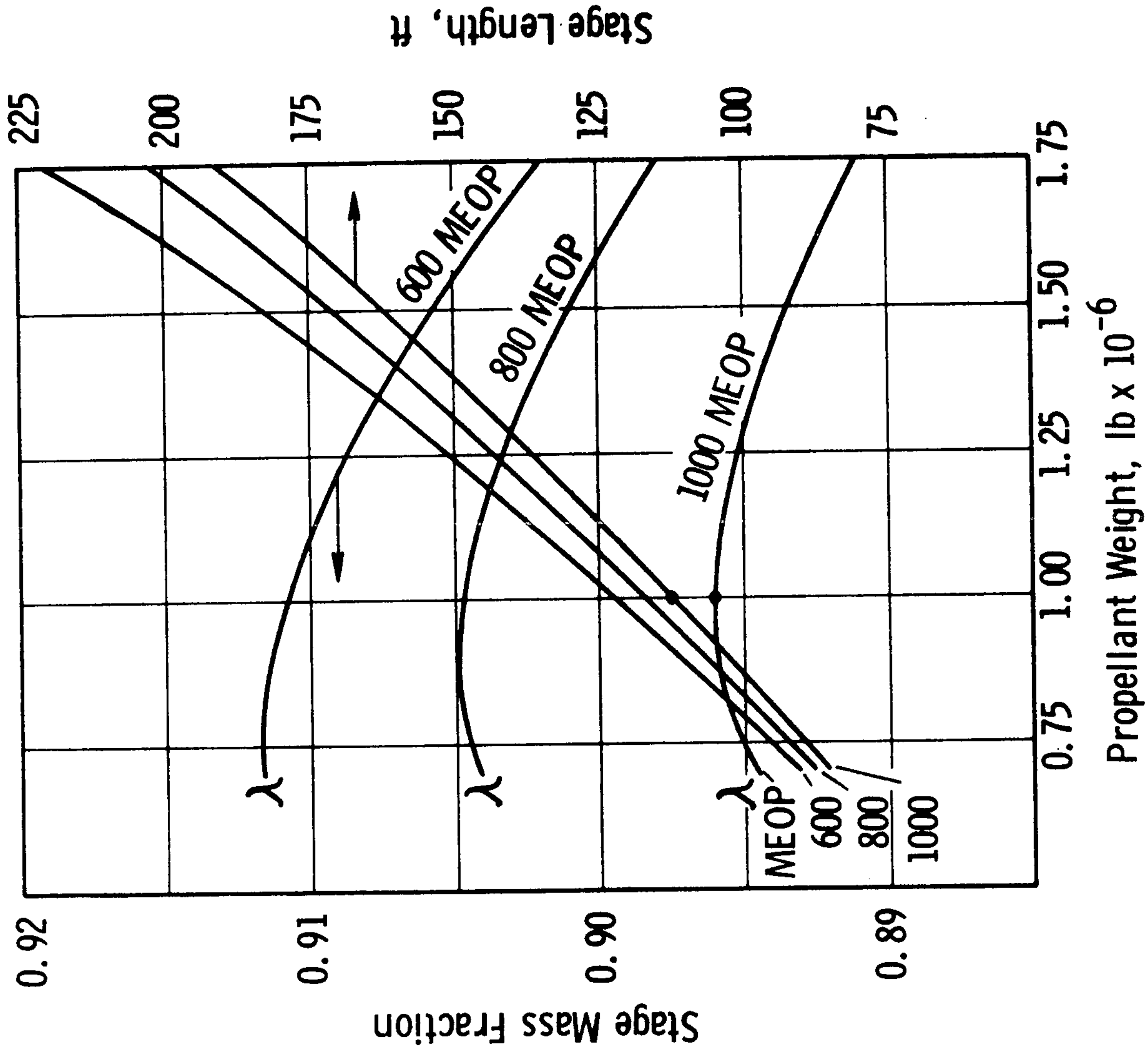
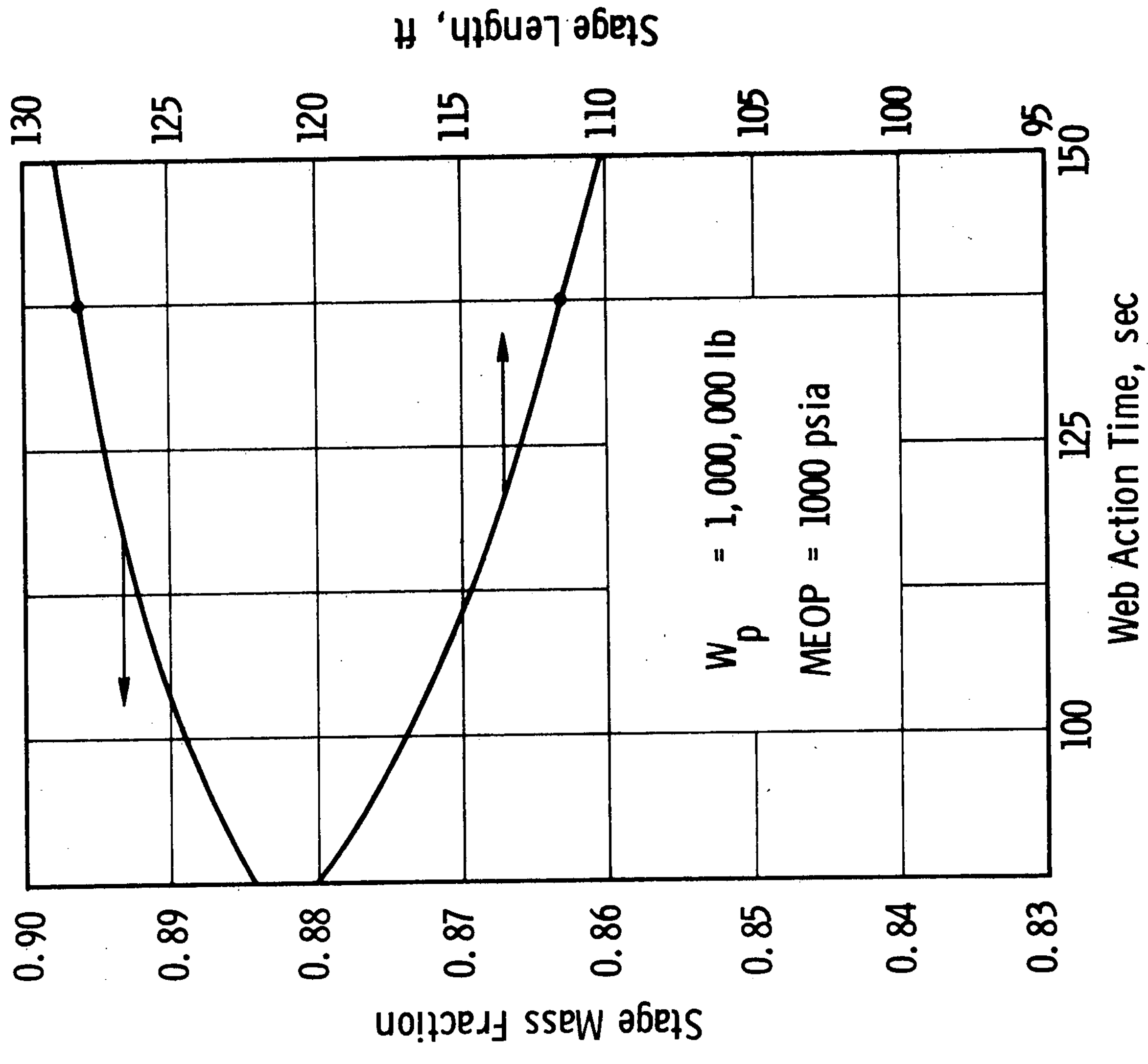

Pressure Decay
Time, millisec
0
25
50
75
100
125
150
175
200
225
Thrust, lbf x 10^-3
Pressure, psia
0
250
500
750
1000
1250
1500
1750
Vent Thrust
Nozzle Thrust
Chamber Pressure

Figure II-37



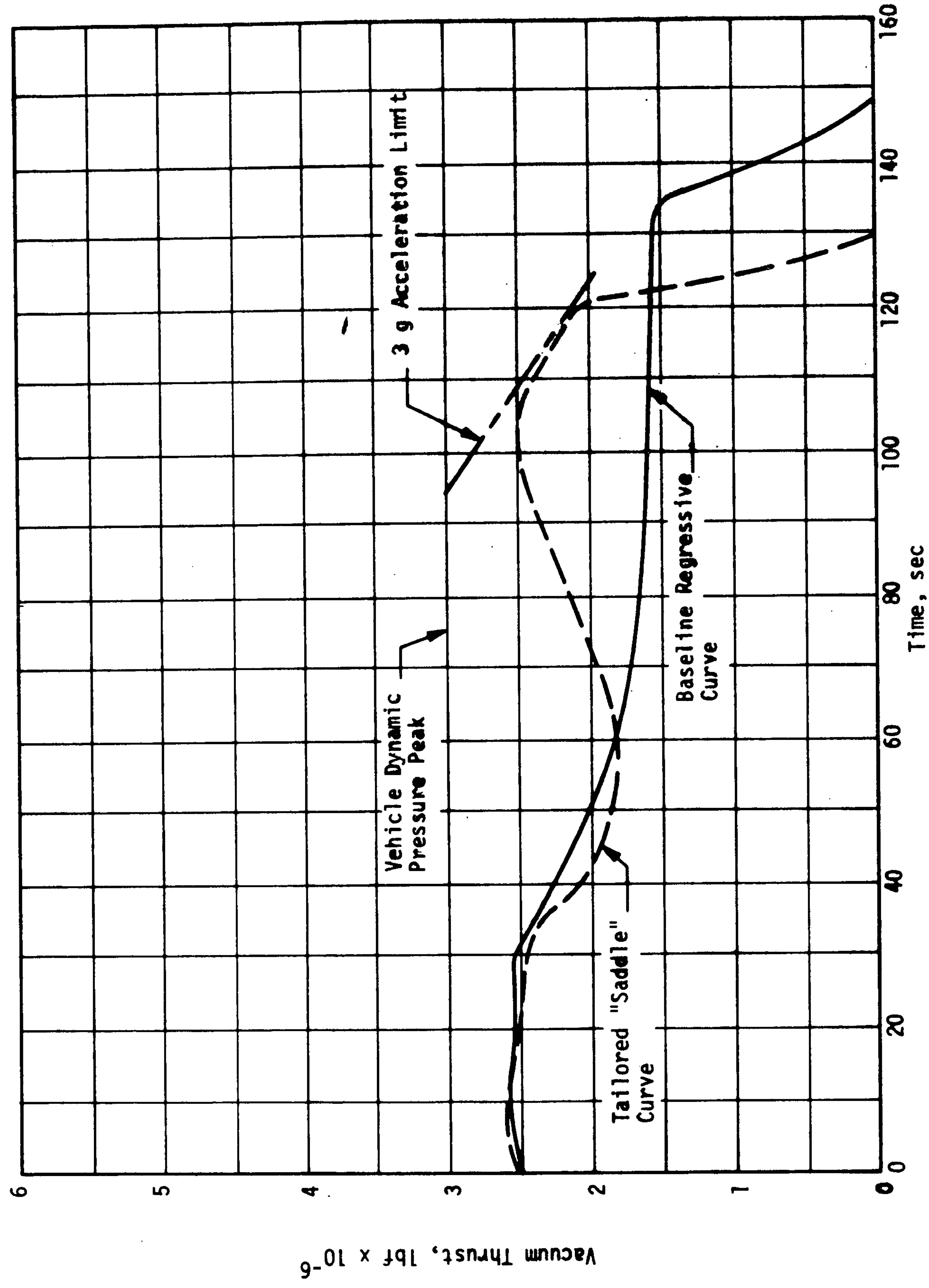
Effect of Propellant Weight on Stage Mass Fraction and Length

Figure II-38



Effect of Burn Time on Stage Mass Fraction and Length

Figure II-39



Comparison of Tailored Thrust Schedule with Baseline

Figure II-40

III. PROGRAM ACQUISITION PLANNING

A. DESIGN, DEVELOPMENT, TEST, AND ENGINEERING (DDT&E)

1. Introduction and Summary

A comprehensive development and man-rating program has been defined that will verify all design and performance requirements of the SRM stage prior to the first manned orbital flight (FMOF). Program emphasis is placed on a design-for-reliability concept with product assurance controls and an effective test program validating the design.

The ground test program will be completed within 36 months (baseline motor; 42 months with TVC) from authority-to-proceed (ATP), with all motor processing and full scale testing being conducted at the Aerojet-Dade Division (A-DD) facility at Homestead, Fla. No new facilities are needed at A-DD to complete the DDT&E program. Modification, refurbishment, and reactivation of this facility can readily be completed prior to the start of manufacturing operations. The location of the A-DD plant enables use of barge transportation of loaded setments to KSC and results in significant cost savings.

All major motor and stage components will be procured from outside suppliers. Maximum incorporation in the booster of components previously qualified for manned-flight programs will be a design criteria.

Throughout this study, it has been an objective to investigate all phases of the program to a level of detail permitting generation of realistic and justifiable cost data. This objective has been achieved.

The general scope of the DDT&E program is as follows:

a. Six full scale static test firings (8 with TVC option)

b. Component development and man-rating test program

III.A. Design, Development, Test, and Engineering (DDT&E) (cont)

c. Delivery of two stages for vehicle structural, dynamic, and integration tests (1 inert; 1 empty)

d. Delivery of six all-up booster stages for flight test program (1 unmanned; 5 manned)

2. <u>Program Objectives</u>

a. Development

The primary objectives of the development phase of the program are to:

(1) Design an SRM booster that meets all shuttle operational requirements.

(2) Verify all manufacturing and processing procedures.

(3) Acquire test data to confirm the motor design.

b. Man-Rating

Objectives of this phase of the program are to:

(1) Qualify all components and subsystems at conditions exceeding the ground and flight environment.

(2) Demonstrate acceptability of manufacturing processes, tooling, and facilities planned for the production program.

(3) Verify, by static firing of the all-up SRM booster, complete and repetitive compliance with all design and performance requirements.

III.A. Design, Development, Test, and Engineering (DDT&E) (cont)

(4) Provide a checkout of flight program AGE and procedures.

3. Schedule

The baseline SRM (no TVC) development program can be completed within 36 months from Authority-to-Proceed (ATP). Addition of a TVC system will add 6 months to the total program span. Delivery of the first set of insulated segment sections is the principal driver on the schedule; 16 to 18 months are quoted as the most probable fabrication period. On this basis, the first development test will be conducted in the twenty-first program month. Figure III-1 shows major program milestones.

The ATP date was selected to permit completion of all motor firings (with TVC) prior to start of flight-test motor processing. The allotted 3-month span between ground tests might be reduced for the last two man-rating motors when the first production cast/cure facility comes on-stream. However, the added complexity of these tests suggests that a conservative approach be taken, and accordingly, no schedule adjustment has been made.

The schedule is realistic and even slightly conservative. If a more accelerated effort is necessary, the following steps can be taken:

a. Order case segment billets prior to the program ATP (during the Design Definition Phase).

b. Provide for a motor processing facility independent of the test site (available facility is planned for both functions).

4. Design and Engineering

The design and engineering effort for the Development and Man-Rating Program will encompass component, subsystems, and systems definition and technical direction from ATP to the Production Program phase-in. The scope of

III.A. Design, Development, Test, and Engineering (DDT&E) (cont)

work and schedule are predicated on the completion of a Design Definition Phase before ATP, so that firm definition of requirements is available. Prototype design drawings for major motor components (case, nozzle, TVC) will be released for procurement within 30 to 60 days after ATP.

The prototype design tasks and supporting analytical studies will be essentially complete within one year after ATP in time for a prototype design review. Subsequent design and engineering tasks will support component, subsystem, and full-scale development test programs. The first year of design activity would be performed exclusively at the Aerojet Sacramento facility. Subsequent design and engineering will phase into the engineering organization to be established at the Dade Division facility over a period of about two years.

Component and subsystem design tasks are listed in Figure III-2 with the necessary supporting analyses indicated. In addition, systems studies will be accomplished as listed below:

Acoustic environment
Exhaust plume heating
Aerodynamic heating
Environmental impact
Safety and reliability
Vehicle interface

All drawings, specifications, and standards will be prepared in accordance with applicable government standards and will be submitted to the customer along with supporting analyses for review and approval prior to implementation.

5. Manufacturing Plan

A detailed manufacturing plan has been prepared defining booster material and hardware requirements, make-or-buy determinations, processing plans, facilities and tooling needs, and schedules. This plan forms the basis for development of the motor manufacturing and processing costs. Key elements of the plan are discussed in the following sections.

a. Site Selection

Facilities exist at the Aerojet-Dade Division for the processing of solid rocket motors of up to 260-in.-diameter. The proximity of the plant to the KSC launch site will minimize transport time and cost. The A-DD site provides the options of either rail or water transport since a navigable canal exists from within the plant site to the Florida Intercoastal Waterway.

b. Process Plans

Detailed plans for processing the full scale motor and igniter were prepared. These plans delineate the sequence and flow of manufacturing operations and are based on specific design details, known material characteristics (cure rates, etc.), and from the experience gained on many other programs utilizing similar (or identical) operations. Each element of the process sequence was considered in detail to establish manpower, tooling, facility, and equipment requirements, and compliance with design criteria.

A cycle time was established for each operation or process sequence and the total time required to produce a loaded SRM determined. Cycle times were based on historical data from similar operations and include allowances for operational efficiency. The motor processing time-line is shown in Figure III-3.

III.A. Design, Development, Test, and Engineering (DDT&E) (cont)

In preparing the process plans, all subtasks pertinent to the prime operations were also defined in detail and tooling, facility, and cycle time requirements established.

c. Make-or-Buy Plan

The motor design was reviewed in detail to determine which components or subsystems could best be manufactured by Aerojet or procured from other manufacturers or suppliers. The basis for selection of in-plant manufacture was simply having a strong competitive capability for making the item under consideration. On this basis, an initial decision was made that the igniter, igniter booster, and the flexseal would be made by Aerojet (in addition to the primary effort of loading and assembly of the motor segments). The igniter is an item which fits ideally within the principal Aerojet product line, and this was an obvious selection. Aerojet has experience in flexseal manufacture (260-in.-dia motor size), and a detailed cost estimate was prepared. Quotes were also obtained from several other sources. The Aerojet price was not the one used in the cost data reported and a firm make-or-buy decision has not been made.

The chamber segments will be fabricated and insulated by a subcontractor. Nozzle assemblies, TVC system, ordnance, structures, and most stage components will likewise be obtained from outside suppliers.

d. Batch Analysis

An analysis of the total propellant material requirement was prepared for the baseline development and production programs. This analysis establishes propellant material losses and test attrition for each phase of the program. Propellant testing and qualification requirements are specified in the Quality Control Plan and include: raw material testing, material lot-combination checkout batches of propellant, and testing of each batch of propellant to be cast into a motor.

III.A. Design, Development, Test, and Engineering (DDT&E) (cont)

The batch analysis also defines propellant materials needed for initial formulation work during the propellant characterization and tailoring phase.

The batch analysis provides a consistent basis for determining material and hardware quantity requirements necessary for obtaining supplier quotes as well as for determination of in-plant processing operations. Separate batch analyses were prepared for the baseline motor and for the propellant-type igniter.

The batch analysis is included as Appendix C.

e. Full Scale Motor Process Plan

Existing facilities at A-DD will be used to manufacture and test the development motors. Reinstallation of equipment and reactivation of the plant will be completed by the fourteenth program month.

Insulated chamber segments will be transferred to the plant on a trailer/tractor from the railhead at Homestead. Mobile cranes, crews, and transport vehicles will be leased for these operations.

Inert chamber operations will be performed in the existing General Process Building (11101) with the chamber segments remaining on the shipping trailers for mobility. The inert operations consist of:

(1) Abrading the internal chamber insulation

(2) Solvent washing and drying of the insulation

(3) Applying and curing the liner

III.A. Design, Development, Test, and Engineering (DDT&E) (cont)

The lined segments will be transported to the existing cast, cure, and test (CCT) facility and prepared for propellant loading.

A tooling mandrel (core), used to mold the grain bore cavity, will be installed. This assembly is then positioned within one of the cast-cure enclosures to be constructed in the CCT caisson for propellant loading. These, and other key processing operations, are shown graphically in Appendix C.

A premix of all propellant ingredients, except the oxidizer (NH_4ClO_4) and the final curing agent, will be prepared in the existing Premix Fuel Facility (11102) and stored in a tankage system to be added to this facility. Premix will be dispensed as necessary for the mixing procedure.

Oxidizer grinding will be accomplished in the existing Grinder Facility (11204) and dispensed into tote-bins with the required amount of unground oxidizer. The tote-bins will be transported to the propellant mix stations, as needed.

The mobile mixer-bowl is first loaded with the required weight of premix (at the Fuel Facility) and transported to the mix-station where the oxidizer and curing agent are added while mixing under vacuum. The completed propellant batches are delivered in their mix-bowls to the casting site where they are loaded into the chamber segments.

The bowls of propellant are positioned on a tooling stand above the prepared chamber segment and connected to a bayonet casting tube. This tube extends to, or slightly below, the surface of propellant already cast into the segment (or to the bottom of the segment if none has been previously cast).

After casting each bowl of propellant, the casting stand is raised to reposition the bayonet casting tube outlet at the new propellant surface.

III.A. Design, Development, Test, and Engineering (DDT&E) (cont)

When the chamber segment is filled to the required level, the casting stand is removed, a cover is installed over the enclosure in which the segment rests, and hot air (115°F) is circulated around the segments to cure the propellant. When the propellant cure is complete, as evidenced by hardness measurements, the core is extracted.

The segments are lifted from the cast enclosure by a derrick (to be reinstalled) and placed onto a tooling stand for radiographic inspection of the cast propellant. An intervening shielding wall will be constructed to the CCT for personnel protection.

The motor will be assembled (nozzle up) onto the test fixture in the center of the CCT caisson (Figure III-4). A leak test of the assembled motor completes the processing operation.

6. Testing

a. Test Program Philosophy

A statistical reliability program at the full-scale motor level is not economically practical nor is it necessary on a technical basis. The simplicity of the basic motor, the proven technology incorporated in the design, and the generous safety margins used combine to reduce the scope of the test program. The requirement becomes one of verifying the design and performance (development phase) and establishing confidence that all stage systems meet mission requirements (man-rating).

Further, it is the operable systems or components (electronics, valves, etc.) that generally are most susceptible to a failure or faulty operation. These components will undergo extensive testing and verification at the bench level before they are qualified and incorporated on the man-rating motor firings.

III.A. Design, Development, Test, and Engineering (DDT&E) (cont)

Therefore, six full scale motor tests (3 development and 3 man-rating) are planned. Arguments could be made to substantiate the need for additional firings, but on a statistical basis there is little to be gained from increasing the man-rating test quantity by 1 or 2 units. However, the complexity of a TVC system and the need for acquiring substantial engineering data, failure simulation and system redundancy capability demonstrations, and the various flight-profile duty-cycles dictates and justifies a more extensive test program. For these reasons, two additional firings are planned if the SRM configuration includes TVC (4 development and 4 man-rating).

Other ground rules which governed design of the test program and which were considered during preparation of test costs were:

(1) There will be one live demonstration of the thrust neutralization system.

(2) Development Motor 3 will be representative of the flight configuration (frozen design).

(3) All subsystems installed on man-rating test motors will be fully qualified.

(4) Ground support equipment (GSE) may be utilized, at least for backup, on the first two motor tests.

(5) The last two man-rating motors will be processed using production facilities and procedures.

(6) With few exceptions, all new hardware will be used on man-rating test motors.

III.A. Design, Development, Test, and Engineering (DDT&E) (cont)

(7) Extensive data on the acoustic, thermal, and exhaust cloud environment will be taken on the first two tests. Only exhaust cloud tracking and fallout sampling will be included on subsequent tests.

b. Full Scale Development Firings

The primary objectives of the development firings are:

(1) Verify acceptable design and performance of all motor and stage systems prior to start of man-rating testing.

(2) Confirm propellant burning rate and specific impulse.

(3) Verify nozzle and case insulation design and material performance.

(4) Establish ignition and tailoff characteristics.

Additional objectives related to the TVC system are:

(1) Verify deflection-vs-torque relationship.

(2) Confirm system meets response and control requirements.

(3) Demonstrate redundancy capability.

Specific test objectives and the configuration of the three full scale motors (4 with TVC) are summarized in Figure III-5.

III.A. Design, Development, Test, and Engineering (DDT&E) (cont)

c. Full Scale Man-Rating Motor Tests

The objective of this phase of the DDT&E program is to demonstrate that the all-up SRM booster stage is fully qualified for flight testing.

To achieve flight readiness status, the full-scale motors to be statically test fired will be, to the maximum extent possible, identical to the flight operational stage. Exceptions to this plan will be items such as:

Nose fairing
Stage attachment structures
Live shaped-charge assemblies
Control and monitoring systems requiring orbiter avionics

The actual mission profile will be closely simulated in each test. TVC duty-cycles (if applicable) and actuation of separation ordnance will be programmed to duplicate typical flight sequences. Simulated malfunctions will be sensed by the flight safety monitoring system with thrust termination and SRM destruct demonstrated through initiation of EBW squibs.

Except for major structural elements (aft support skirt, etc.), all new hardware will be used on man-rating motors. All systems will represent bench-test qualified designs, having successfully been demonstrated on the last development firing.

Three full-scale tests are planned for the baseline design and four for the TVC alternative.

d. Static Firing Plan

Full-scale SRM testing will be conducted in a concrete caisson (cast, cure, and test facility) at A-DD. This facility is equipped with

III.A. Design, Development, Test, and Engineering (DDT&E) (cont)

a thrust-bearing spacer capable of reacting a total of 20 million lbf thrust-weight load. The spacer will be modified to accommodate the length of the 156-in.-dia motor. Attachment plates are installed in the wall of the caisson at appropriate locations for the reaction of conventional side force (F_x and F_z) imposed during motor TVC system operation. Fixturing devices will connect these plates to the motor at the forward and aft end to provide for measurement of those forces. In addition, a hydraulically operated, controlled decoupling, calibration system will be provided which will be capable of applying and measuring a known side force either prior to or during any full-scale motor test with TVC.

Main motor thrust will be measured by an available BLH load cell. The load cell will be isolated from bending or side force moments by a shroud flexure. TVC side force measurement systems will include modular flexure isolation for the load cells.

Full-scale motor demonstration of the thrust termination system (last development firing) will incorporate structural steel ducting in the caisson to collect and channel exhaust gases over to and up the wall of the caisson.

A posttest internal quench system will be used on all tests. A moving A-frame/bridge assembly will be rolled over the motor nozzle after tailoff and a telescoping pipe section will introduce quench water to the motor interior. This will enable a more valid assessment of insulation performance by extinguishing the posttest burning or charring of the insulation. Overheating of the case is also prevented.

To protect against motor escape, should a major motor forward end malfunction occur, the motor will be retained in the caisson by means of a system of 12 cable assemblies attached to the motor aft skirt (test) extension and anchored to the internal wall of the caisson.

The instrumentation capability at A-DD will consist of the following:

72 channels of force, pressure or strain data

24 channels of temperature data (thermocouples; calorimeters) (may be increased to 120 channels by sampling)

24 channels of position data (linear potentiometers; LVDT)

3 closed circuit TV systems

1 thrust vector control system

28 channel analog tape recorder

1 digital data acquisition system

6 oscillograph recorders

6 strip chart recorders

Of prime importance is the application of a sensor based computing system to acquire digital data. Data will be recorded on disc packs and delivered to the Aerojet data processing center where it will be processed into engineering unit listings, performance calculation listings, and X-Y plots. During the test firing the data acquisition system will be capable of automatically sequencing countdown operations.

Each phase of the full-scale motor test operation has been examined in detail so that an accurate cost estimate could be prepared. Manpower, special test equipment (STE), and facility modification requirements were defined. Aerojet's 260-SL test experience at A-DD provides a useful baseline upon which to establish costing criteria. In addition, the multitude of large and complex solid motors tested at Aerojet, Sacramento, including second and third stage Minuteman, first and second stage Polaris, and 100-in.-dia segmented rocket motors, further added to the cost background data that is available.

III.A. Design, Development, Test, and Engineering (DDT&E) (cont)

Included as Appendix D is a portion of the planning documentation which was used to generate the test cost estimate. Descriptions of STE items, instrumentation systems and expendable material requirements may be found therein, as well as specific task definitions. All cost figures and man-hour estimates have been deleted, but are available for NASA examination on request.

e. Component Testing

(1) Ignition System

During the development phase, the initiator and booster subassembly will be statically fired (4 units) to characterize the pressure-time envelope. This unit consists of a standard Minuteman second stage igniter with dual EBW squibs. The Minuteman igniter is qualified with a safe/arm device presently, however, substitution of EBW squibs will have a negligible effect on igniter performance. Thus, a minimal design verification of this subassembly is required.

Six complete igniter assemblies will be fired during development to verify that performance and materials meet design requirements. Internal pressure measurements will be recorded and analyzed. If design modifications are required, three additional tests will be conducted prior to the man-rating tests.

During the man-rating phase, an additional six igniters will be tested. Environmental testing to simulate service conditions will be conducted prior to firing of the units. These tests will include temperature and humidity cycling, shock, transportation vibration, and aging. Units will be fired in pairs using firing circuitry duplicating the shuttle system to establish simultaneity variance. This test program is discussed in more detail in the planning documentation of Appendix C.

III.A. Design, Development, Test, and Engineering (DDT&E) (cont)

(2) Case Segments

The first prototype 156-in.-dia case center segment will be hydrostatically tested to failure. Strain data and acoustic emission signals will be recorded during the test. The fabrication process, design margins, and NDT procedures will be verified. If recovery of SRM cases and re-use is a program requirement, the case section will initially be subjected to multiple (150% of the proposed life-cycle magnitude) cycles at the proof test pressure level to demonstrate the capability of the case to be reused successfully and the ability of the acoustic emission monitoring system to detect flaw growth. Repair of the case may be accomplished between pressure cycles if flaw size approaches the calculated critical dimension.

(3) Flexseal

Two flexseals will be structurally and functionally tested to verify design, materials, and fabrication methods selected for the production item. Test procedures and tooling will be patterned on a successful test program completed on two seals representative of a 260-in.-dia motor design. (Reported in NASA CR 72889, Contract NAS3-12049). Test details and a sketch of the test fixture are presented in Appendix C. Data will be obtained on seal axial deflection, rotational torque-vs-degree of deflection angle, structural integrity at 1.25 x motor MEOP pressure and under conditions of cyclic fatigue. One seal will be tested to destruction. (These tests are only applicable if a TVC system is included on the SRM).

(4) TVC System (Optional)

Developmental testing of the TVC system will be directed primarily towards verifying that performance requirements are met or exceeded. Maximum deflection, dynamic response, hysterisis, null-stability, control sensitivity, and resolution are a few of the parameters to be

III.A. Design, Development, Test, and Engineering (DDT&E) (cont)

characterized. Extended duty-cycle capability, redundancy, and fail-safe provisions also will be confirmed. Components that could be sensitive to flight vibration or acceleration environments will be tested under these conditions prior to initiation of formal man-rating qualification.

Six complete TVC systems, representing the final flight configuration, will be subjected to extensive environmental testing during the man-rating test program. Tests will be conducted at the component, subsystem, and system level. The specific tests and exposure levels will be defined during the Design Definition Phase and approved by the NASA Program Manager. As a minimum, the tests will include:

Ground handling shocks (packaged components)

Transportation (low-frequency sine-vibration, packaged)

Temperature and humidity cycling

Flight vibration (combined sine and random)

Acoustical

Vehicle acceleration (sustained static g-load)

Altitude (to pressure equivalent to 200,000 ft)

Acceptable operation will be demonstrated after exposure to the ground environments and during exposure to the flight conditions. The final test in the bench-level qualification program will include an all-up assembled system, mounted to duplicate the SRM installation, tested under the most critical combined operational conditions (vibration and acoustical). Operation of all systems at performance levels in excess of mission requirements will be verified.

III.A. Design, Development, Test, and Engineering (DDT&E) (cont)

(5) Ordnance Systems

Development testing of pyrotechnic components will be oriented principally towards establishing of proper sizing and stand-off distances of shaped charge assemblies. Steel plates, representative of case sections, will be provided to the system supplier to use in the actual cutting depth evaluations. Other system elements such as EBW squibs, confined-detonating-fuses (CDF) and initiation command modules (ICM), or firing units, are available as off-the-shelf items and have previously been qualified to Apollo program specifications. A minimum of recertification testing should be required on these components.

After destruct and thrust neutralization shaped-charge parameters have been established and verified, repeated firing tests will be conducted on partial sections to define response time variability limits and reproducibility of the cutting mode and depth.

(a) Thrust Neutralization (TN) System Demonstration

The prototype production thrust neutralization system will be installed on a 156-in.-dia motor case (single center segment). A heavy-weight nozzle closure and igniter-boss plug will provide pressure vessel integrity. The test chamber will be pressurized to 1000 psi and the TN system actuated. This test will permit data acquisition on the dynamics of the TN port ejection, instantaneous overpressures created, time from command to ejection, and simultaneity of port removal. The center segment may be used for a demonstration of the destruct system if this is later determined to be necessary. The pressurized case TN system test will be conducted at Aerojet, Sacramento, prior to the incorporation of the system on a live motor test at A-DD.

III.A. Design, Development, Test, and Engineering (DDT&E) (cont)

(b) Full-Scale Motor Thrust Neutralization Testing

The all-up "hot" test of the TN system mentioned above will be a part of the last development firing. The nozzle-up orientation of the motor in the CCT (Figure III-6) does not facilitate acquisition of all data that would be desirable to have for complete definition of the pressure venting sequence (for example, motion picture coverage of the TN port-cover ejection, thermal and pressure data in the area where the orbiter would be, etc.).

Because of the potential for severe facility damage (due to residual propellant burning), the initiation of the firing command to the TN shaped charges would be programmed for late in the firing, just prior to web-burnout. An above ground test, preferably nozzle-down, or possibly a horizontal firing, would be more satisfactory from a data acquisition standpoint. However, this would require a substantial investment in new facilities.

(c) Man-Rating of Ordnance Components

Testing will concentrate on the shaped-charge assemblies, as all other portions of the various ordnance systems are now man-rated for Apollo. However, if the shuttle boost phase dynamic environment is more severe than the test levels of the original qualification specification, all items will be requalified at the more stringent condition.

The various ground and flight environments listed under TVC system testing will be the basis of the man-rating qualification program. A minimum of 12 complete TN sets, mounted to simulate booster installation, will be tested. Emphasis will be placed on vibration, altitude, and humidity exposure. In the absence of actual test requirements, cost estimates were based on test methods specified in MIL-STD-810B.

III.A. Design, Development, Test, and Engineering (DDT&E) (cont)

(6) Instrumentation and Electrical Components

Transducers will be selected which have previously been qualified for manned flight vehicles and minimum requalification will be required. Signal conditioning and multiplexing units will undergo the typical combined environment tests described for other systems with functional performance being demonstrated during testing. Test costs for flight qualification were included in the system quotes obtained from potential suppliers.

(7) Stage Structural Components

Stage attachment structures and the aft support skirt will be tested to levels exceeding the design loads calculated for the worst service condition. Compression, bending and shear loads will be applied by hydraulic jacks. Strain data will be obtained to assure material yield strengths are not exceeded and to verify the calculated deflection of critical members. If recovery and reuse is a program requirement, these tests will be repeated to duplicate the service life-cycle. Acoustic emission techniques will be used to detect onset of flaw propagation.

7. <u>Product Assurance and Reliability</u>

a. Quality Assurance Plan

The quality assurance plan will incorporate state-of-the-art and advanced product verification methods consistent with design, man-rating, and cost effectiveness requirements of the program. The quality plan will be implemented during DDT&E as well as the production phase.

The methods that will be used are primarily:

Raw materials and process controls at each Aerojet supplier

III.A. Design, Development, Test, and Engineering (DDT&E) (cont)

Fabrication control and product inspection at major assembly levels

Integrated assembly verification of motor segments and completed assemblies

Acceptance testing of operable components and subsystems

The Booster Quality Assurance Plan will define the detailed inspection, NDT, and documentation requirements for all elements of the program, as shown in the block diagram of Figure III- 7. A typical sequence of inspection procedures that various motor/stage systems will be subjected to are indicated in Figure III-8.

Each selected supplier of major components will be served by a resident Aerojet quality engineer to ensure continued maintenance of inspection procedures and documentation. When component and major assemblies are completed, Aerojet will conduct independent verification of critical characteristics and dimensional configurations.

To detect any errors in process or materials control, a comprehensive program of propellant verification will be imposed. Complete lab analysis will be conducted on each batch of propellant from submix to final formulation. Cure rates and final propellant physical and mechanical properties are also 100% verified to be within allowable limits. Each cured segment is final inspected by radiographic and ultrasonic methods. A complete leak check and systems verification testing after motor assembly complete the inspection sequence.

The quality attained during the entire production cycle will be verifiable by NASA and prime contractors through a comprehensive documentation program that provides checks of all critical parameters and processes.

III.A. Design, Development, Test, and Engineering (DDT&E) (cont)

b. Functional Description

The Product Assurance operating organization is responsible for verification of product quality at all levels of design, fabrication, assembly and test. Manning and special equipment requirements for each of the operating departments were determined for the booster program cost estimate on the basis of the functional responsibilities described below.

(1) Quality Engineering

Basic quality engineering disciplines will be initiated to establish program quality requirements consistent with NHB 5300.4 (1B). Inspection planning, procurement control MRB activity, and process control functions will be conducted.

(2) NDT/Gage and Tool Design

Design and fabrication control of all master and field gaging, inspection tooling and NDT systems will be accomplished. Nondestructive test methods for chamber proof testing, propellant and insulation inspection and material verification will be developed and monitored.

(3) Supplier Source Control

On-site inspection and surveillance functions at all major suppliers' facilities will be performed. Suppliers' quality control systems, product quality trends and method of operation will be continually reviewed and approved when applicable. Discrepancy dispositions will be coordinated with A-DD Quality Engineering and customer representatives. On-site product acceptance will be based on approval of the suppliers' manufacturing and inspection documentation and concurrent Aerojet participation at established inspection stop-points.

III.A. Design, Development, Test, and Engineering (DDT&E) (cont)

(4) Inspection

The inspection department will be the largest operating section in the Product Assurance organization, reaching a manning level of 81 persons in 1984. The basic functions of dimensional, visual, NDT, and other inspection procedures are performed by this group.

(5) Analytical Chemical Laboratory

Receiving inspection and acceptance testing of chemical raw materials, including propellant and liner ingredients, insulation, adhesives, and paint will be conducted. In-process acceptance testing of propellant submix, premix, uncured and cured propellant from each batch is also a laboratory responsibility. Parameters to be verified are density, burning rate, cure rate, and physical properties.

(6) Reliability

The Booster Reliability Engineering and Analysis section will participate in all phases of the program, from initial design to final acceptance testing. Some key elements of the reliability functions are summarized below.

(a) Perform and maintain, through periodic updating, Booster Systems Effectiveness Analysis. This work will determine performance margins available for safety, reliability requirements, environmental and aging program requirements.

(b) Assist in the performance of requirement vs capability (R//C) analysis throughout development and production programs.

III.A. Design, Development, Test, and Engineering (DDT&E) (cont)

(c) Perform failure modes effects and criticality analysis; determine and assure corrective action.

(d) Analyze all phases of performance on full scale and component qualification tests for feedback into R//C analysis.

(e) Provide and maintain, through routine update, all statistical data for R//C analysis, design and manrating reviews. (Reliability data pool)

(f) Assure that all manrating and other reliability design and test requirements are met.

(g) Determine requirements for further design effort, failure and abort systems, fail-safe features, and redundancy systems. Assure compliance with these requirements.

c. NDT Plan

A nondestructive testing program will be established for all phases of motor development and production to assure motor, component, and assembly integrity. The basic features of this plan are described below for the major motor elements.

<u>Forged steel rings</u> will be subjected to ultrasonic inspection with both shear and longitudinal waves for detecting all internal discontinuities.

<u>Chamber welds</u> (if used) will be ultrasonic and X-ray inspected for shrinkage cracks, slag inclusions, lack of fusion porosity, and lack of penetration. The welds also will be subjected to MPI for detecting surface or near surface defects. Machined surfaces will be examined by eddy current and by dye penetrant for detecting surface defects.

III.A. Design, Development, Test, and Engineering (DDT&E) (cont)

The chamber segments will be hydrostatically tested using accelerometers to detect acoustic emissions from undetected flaws. Stress wave analysis triangulation techniques will be applied to locate the flaw area for appropriate corrective action.

FM ultrasonic techniques will be used to detect insulation internal defects; insulation-to-case bond evaluation will be performed utilizing standard pulse-echo ultrasonic equipment

Tape-wrapped nozzle components will be radiographically inspected to detect internal delaminations and unbondedness between components. Laminates in the flexseal will be inspected ultrasonically to assure bonding between layers. Sonic tests will be imposed on the glass structural overwrap to assure the structure is free of delaminations and that bonding between composites is sound.

Igniter grains will be X-rayed for voids and cracks prior to bonding into the igniter case segments and again after grain installation and assembly.

Each loaded end-segment will be inspected using tangential X-ray to verify the steel-insulation bonding, insulation-propellant bonds, and adjacent propellant quality. Center segment propellant and bonding quality will be verified by X-ray scanning and low-frequency ultrasonic through-transmission techniques.

III. Program (cont)

B. PRODUCTION PROGRAM

The space shuttle booster production program was designed in accordance with the delivery requirements of the baseline 440-flight traffic model. The peak delivery rate is reached in 1985, when 120 SRM boosters (parallel-burn configuration) will be required. Ten motors will complete the production process each month. The incremental build-up to this rate allows an orderly addition of needed personnel, equipment, and facilities.

The production program is essentially a motor manufacturing and quality assurance effort. Transportation requirements and the KSC launch support operation are the other main program elements. These areas (with the exception of quality assurance, which will be conducted in the same manner as during DDT&E) are discussed in the following sections to provide an understanding of the Aerojet approach and to indicate the level of detail considered during the cost study.

The production milestone schedule is shown in Figure III-9 . To meet the first production booster delivery date, long-lead time items must be ordered at the completion of the full-scale motor static test program.

1. Procurement and Production Plan

a. Components

Hardware for all major components of the motor will be procured from subcontractors.

Processing and subassembly of the following major components will be subcontracted:

III.B. Production Program (cont)

Chamber insulation

Nozzle and exit cone assembly

Ordnance systems

Electrical and instrumentation systems

Flight control and hydraulic systems

Stage structural components

The igniter will be fabricated at Aerojet Solid Propulsion Company, Sacramento, California.

Most subsystems will be installed on the motor segments at the Aerojet Dade Division (A-DD) facility. However, certain components will be delivered directly to the launch site. Items to be delivered there are:

Nose section subassembly and aft structural skirt subassembly

Aft exit cone section

Portions of the ordnance system

Portions of the electrical system, batteries, cables, raceway cover, etc.)

Stage attachment/separation structures

b. Process and Assembly Sequence

The internally insulated chamber is received by railroad car at A-DD. Shipping covers are removed and the insulation abraded by grit blasting. A liner material is applied to the prepared insulation surface and cured to provide a reliable propellant bonding surface. The chamber segments are assembled for propellant casting by placing them in the vertical attitude and positioning them on a casting base. The inert operations will span an eleven-day period.

III.B. Production Program (cont)

A casting core is installed into the lined segment and the assembly positioned on its transporter under the casting stand. Mixing bowls of propellant are positioned on the casting stand above the segment. Propellant is cast at ambient pressure through a bayonet maintained at or just below the propellant surface. Cure of the propellant is accomplished in ten days at 110°F. Upon completion of cure, the casting core is extracted and cleaned for reuse. The segment is then transported to the nondestructive test facility. Sketches showing principal operations of the motor manufacturing sequence are included in Appendix C.

In the final assembly building, the igniter is installed in the forward segment and the nozzle on the aft segment. Other subsystem hardware is installed, final inspections and checkouts of the segments and subsystems are performed, and final painting of the segment is accomplished. Transportation covers are installed and the motor segment set is transported to the shipping and storage building. The entire motor processing sequence will be accomplished in 36 days, as shown in Figure III-10.

In the shipping building, segments are placed with the forward end up on a shipping pallet on the barge deck. Environmental covers and monitoring equipment is installed. Two complete SRM sets will be shipped on each barge trip.

c. Processing Facilities (A-DD)

SRM production facility requirements have been established. Existing and modified facilities used during the development phase will be supplemented to enable meeting the propellant processing motor delivery rates prescribed by the 440 flight traffic model.

III.B. Production Program (cont)

Design and construction lead times have been established for each new facility item on the basis of past experience for similar type construction and the need date for the facility to be on-stream. New facilities will be added incrementally to provide for a gradual build-up of capacity to peak delivery rates. Facilities, which are rate-limited or explosive load-limited, will be constructed as the program delivery schedule and rate demands. Other facilities have been timephased to the various construction increments on the basis of cost, size, and need date.

Figure III-11 summarizes all facilities that will be needed at A-DD to manufacture the SRM booster stage. An overall layout of the A-DD facility is shown in Figure III-12. A layout of each new facility was made to determine the square footage requirement, overhead clearances, lifting devices needed, and all other special equipment which would be included in the building. Sketches of these facilities are shown in Appendix C. The facility cost estimate was prepared using these basic design criteria. Utilities, roads, site-improvement and A&E costs were included. The level of detail considered in preparing the cost data may be seen in the engineering estimates shown in Appendix D. Cost data information will be available for NASA review upon request.

d. Production Tooling

Separate development and production tooling plans have been prepared. The production plan provides for usage of all available developmental tooling wherever practical.

Concepts of individual items of tooling as specified in the process plan, have been generated and sketches prepared to facilitate costing and visualization of the process. Preliminary stress analyses have been performed on all major handling tools and fixtures to ensure proper sizing.

III.B. Production Program (cont)

Design and fabrication lead times have been established for tooling items on the basis of experience with identical or similar type and size of tools. The quantity of each tool required was determined from tool use span times and by the process schedule requirements. Incremental tool procurement requirements were defined in accordance with motor delivery requirements.

The tooling and equipment needed for the total program is listed in Appendix C. Sketches showing design concepts are also included therein.

2. Transportation Plan

A summary of the planned mode the transportation of major SRM items is presented in Figure III-13.

Although both rail and barge shipment of loaded SRM segments from A-DD to KSC is feasible, barge transportation was selected as the most desirable method for the following reasons:

a. The largest existing railcars suitable for use (FD cars) have a 250,000-lb weight limitation which effectively limits segment size.

b. Rail shipment dictates horizontal positioning of the segment on the car, necessitating several expensive shipping cradles and inverting operations.

c. Using published rail transportation rates, the recurring shipping costs are over $12 million more by rail than by barge.

d. Barge shipment is compatible with both the A-DD and KSC operational sequence and facility lay-out.

III.B. Production Program (cont)

An extension of the railhead from Homestead, Florida to the manufacturing site is planned to enable efficient movement of the (large) in-coming volume of motor components (principally case and nozzle sections) and propellant raw materials. Homestead is served by both the Florida East Coast and the Seaboard Coastline railways. About ten miles of new track is required, five of which would be on Aerojet-owned property.

Under the direction of the Army Corps of Engineers, a canal was dredged on Aerojet property to provide access to the Intercoastal Waterway. One hundred feet wide and 12-ft deep, the canal (C-111) is part of the flood control project of the Central and South Florida Flood Control District. A company-financed canal was also dredged from Flat Point to Barnes Sound in the Intracoastal Waterway. This portion has been dredged with a 90 ft width at the bottom and 100 ft width at the top. The controlling depth of this portion is 6.51 ft and 6.08 ft at average high and low tides, respectively. Water of this depth would require the use of a shallow draft tug.

There is an earth filled salt water plug above the Bascule Bridge on Highway U.S. No. 1. However, for the traffic rates required, Aerojet would install a salt water lock at this point. An inflatable version of such a lock has been costed and included in the transportation cost data. The NASA Transportation Office in Washington has advised that there are four barges that may be available for SRM transportation.

The Poseidon and Orion are both covered barges; each one is 41-ft, 6-in. wide by 192-ft long and has an allowable weight of 2,215 long tons. Each barge has it's own ballasting system enabling it to displace from 3 to 13 ft of water, depending on the existing requirements.

III.B. Production Program (cont)

The Little Lake and Pearl River are both open barges; each one is 44-ft wide by 210-ft long and has an allowable weight of 2,415 long tons.

For purposes of cost estimating, it was assumed that these barges would not be available and the cost of two new vessels was included.

To use barge shipment, it is necessary to find a suitable vessel that can navigate the shallow portion of the canal. Assurance has been given by tug boat operators in Ft. Lauderdale that such vessels are available.

Tug boats operating on the Intracoastal Waterway can be rented on a full-time basis for \$850 per day or leased on an annual basis for \$297,000. These rates include two crews, fuel and all associated expenses. These prices were used to determine recurring SRM shipment costs. Two tugs are needed full time during the 1984-87 period.

Barges moving in the Intracoastal Waterway average between five and six nautical miles per hour. Two tugs must accompany each barge if they are covered. Outside the Intracoastal Waterway, the speed is approximately 30% to 50% greater, and only one tug is required. This route is preferable, except in conditions of heavy seas.

3. <u>Launch Support Operations</u>

An analysis was conducted to define the transportation, handling, storage, assembly and checkout requirements of a segmented 156-in.-dia solid rocket motor (SRM). The baseline booster system considered would include two 156-in.-dia SRMs (parallel-burn configuration) of 1,000,000 lb propellant each. The SRM/stage unit consists of:

III.B. Production Program (cont)

a. Motor forward segment containing the forward skirt extension, ignition system, and thrust neutralization system

b. Two center segments

c. Motor aft segment assembly, including the submerged nozzle and forward exit cone, TVC system, instrumentation items and aft support skirt.

d. Aft exit cone section

e. Electrical control/cabling

f. All-ordnance destruct system

g. Flight safety assurance/instrumentation system

h. Nose fairing, raceways, structural attachments

For the purpose of this study, it was assumed that the loaded motor segments would be transported in the vertical position by barge from the Aerojet-Dade Division (A-DD), Homestead, Florida to KSC. In addition, it was established that the following operations would be conducted at the manufacturing site prior to motor segment shipment:

a. Motor ignition system installed in the forward segment.

b. Thrust vector control (TVC) system fully installed and checked out.

c. Aft skirt extension attached to the aft segment.

III.B. Production Program (cont)

d. Instrumentation sensors (thermocouples, transducers, etc.) and electronics installed and cable harnesses connected and continuity verified.

The primary objective of the study was to define, for costing purposes, the equipment (AGE), operations and personnel required to provide an assembled and checked-out booster stage ready for mating with the orbitor.

a. Receiving and Storage

Upon reaching the designated KSC storage facility, forward-end handling rings will be installed on each segment. The segment will be transferred by hoist and stored vertically on the shipping pallets. Handling end rings will remain with the segments.

The motor segments will be stored in a new motor storage facility (described elsewhere) in the vertical position. During the storage period, the respective segment handling end rings and shipping pallets will remain with the segment. It was assumed that six complete motors could be stored simultaneously in this facility. The storage building will be capable of maintaining specified motor temperature requirements. Quantity/distance safety aspects of the storage site will be evaluated on the basis of a 0% TNT equivalent value for the total propellant weight.

All receiving inspections of motor components and segments will be conducted in the SRM storage building, thereby relieving the requirement for an additional facility and reducing handling time within the VAB.

Inspection of the loaded segments will consist of a visual examination of the propellant grain, propellant-to-insulation bonds,

III.B. Production Program (cont)

and insulation-to-case bonds. If the transportation environmental monitoring instrumentation records any dynamic loads exceeding the established limits, or if the visual inspection indicates uncertainties in bond condition, an ultrasonic inspection of the entire segment or motor will be conducted.

Operable stage subsystems will be functionally verified to specification requirements prior to assignment to bonded storage. All cable harnesses will be checked for continuity and proper isolation from ground. Inert components, such as exit cone extension and structural attachments (acceptance checked at the supplier), will be inspected for shipping damage only.

b. Assembly and Checkout

(1) Motor Assembly

Each motor segment will be processed, inspected and accepted at A-DD prior to delivery to KSC. The SRM forward segments will be shipped with ignition and thrust termination ordnance installed (less electrical connections). The motor aft segment will be shipped with the TVC system completely installed and checked out. The aft skirt extension will also be installed. The aft exit-cone section will be installed at KSC. The base support structure may be installed at A-DD or KSC, depending on which scheme fits best with other KSC operations and facilities. Base heat insulation will be installed during motor build-up at KSC.

The motor segments will be transferred from storage to the VAB by rail car and unloaded in the transfer aisle. Shipping covers and attach fasteners securing the shipping pallet to the support ring of the aft segment will be removed. The segment will be hoisted by the forward end handling ring and transferred to the modified launch umbilical tower (LUT) where it

III.B. Production Program (cont)

will be positioned and aligned. The forward end handling ring will then be removed from the segment. The shipping pallet and end ring will be returned to the storage facility for recyling into the manufacturing sequence.

The first center segment, with forward end ring attached, will be hoisted from its shipping pallet, transferred to the LUT, and mated with the previously installed motor aft segment. The segment joint retaining pins will be installed, the forward end ring retaining pins removed, and the end ring hoisted from the motor segment. The end ring and shipping pallet will be transferred to storage for recycling.

The erection and assembly process is repeated for the remaining center segment and the forward segment.

(2) Motor Leak Check

Proof of the integrity of all motor segment joints and seals will be obtained as soon in the assembly sequence as possible. This will prevent loss of time and manpower in the duplication of any assembly operation, which would be negated if the leak check were conducted downstream in the assembly sequence.

The nozzle throat environmental cover will be removed and the leak test plug secured in place. Nitrogen and tracer gas (facility supply) pressurization lines are attached to the leakage test set and to the nozzle plug. The motor is then pressurized to the specified test pressure (about 30 psi) with the proper ratio of nitrogen and tracer gas. All joints and seals are then inspected with the tracer gas detector (a component part of the leakage test set) for evidence of leakage. Upon completion, the motor is depressurized. During this process, all test gases are vented outside of the assembly building. The nozzle plug is removed and the environmental cover replaced.

III.B. Production Program (cont)

(3) Nozzle Exit Cone Extension Installation

The nozzle exit-cone extension is shipped to KSC separate from the motor segments. During motor segment mating, the exit cone extension will be transported to the VAB and unloaded in the transfer aisle. The shipping containers will be removed and the sections again visually examined for evidence of transport damage.

Because of the weight and size of the nozzle exit cone extension, a special installation fixture is required for assembly. The exit cone will be placed in the fixture and the assembly positioned under, and in-line with the nozzle. The cone is then raised into position and the attach fasteners installed.

(4) Exit Cone Extension/Nozzle Interface Leak Check

The bolted joint used to secure the exit cone extension to the nozzle throat extension section will be leak checked for integrity. To accomplish this check, a leak check fixture will be provided. The fixture will consist of a conical ring installed inside the nozzle exit cone. The fixture will straddle the exit cone joint and form a chamber that will be pressurized using a tracer gas and the leakage test set.

(5) Install Ordnance Destruct System

The portion of the destruct system that is installed in the motor raceway (linear shape-charges) will be inspected for evidence of shipping damage and delivered to the VAB transfer area. The live and inert components will then be unpackaged, transported to the LUT, and positioned in the motor raceway; transfer blocks between LSC sections will be mated. All

III.B. Production Program (cont)

attach fasteners will be installed and the assembly given a final inspection. A foam strip will be positioned over the destruct system live components to provide protection to these items during subsequent assembly operations. The remainder of the destruct system (electrical cabling) will be installed downstream in the motor assembly sequence.

(6) Install and Checkout Operational Electrical Cable Set

The operational electrical cable set will be visually inspected and transferred from storage to the VAB. The cables will be transferred to the LUT and positioned in the raceway. Appropriate attach fasteners will be installed. All electrical connectors will be mated. Proper connector mating, conductor continuity and shield grounding will be checked utilizing the electrical test set.

(7) Install and Checkout Flight Safety Assurance/Instrumentation

The flight safety assurance/instrumentation cable set will be visually inspected and transferred to the VAB. The cable set will be installed in the raceway and all connectors mated. A functional check of all transducers will be accomplished using the instrumentation test set. Transducers will be checked for proper output in response to a calibration step input, conductor-to-shield isolation, and shield-to-shield isolation.

(8) Align Nozzle/TVC System

The nozzle alignment fixture will be positioned under the nozzle cone extension. A target will be installed in the nozzle throat and at the aft end of the first extension section. Proper positioning of the alignment fixture will be accomplished using predetermined pick-off

III.B. Production Program (cont)

points located on the motor base support ring. The TVC system will be activated using the TVC test set and commanded to the null position. The nozzle will be calibrated to the null position using the alignment fixture which will feature a tooling laser to sight the previously installed targets. Any required adjustments to the actuator rods will be made and secured. The nozzle/TVC system will then be commanded in increments to the full deflected position to insure free, smooth, and accurate response. Ground support hydraulic and electrical supply systems will be used.

(9) Install Base Heat Insulation

The base heat insulation kit will be inventoried, visually inspected, and transported to the VAB. The kit will consist primarily of premolded insulative sections. The insulative sections will be positioned and bonded in place. The base heat installation/removal kit will be used to accomplish this operation.

(10) Ordnance Component Verification

After installation and voltage checks are completed on the ordnance battery, all EBW initiation command modules will be functionally checked using the ordnance device test set. Safing, arming, charging and firing commands will be programmed and proper response verified. Simulated squibs will replace live ordnance for these checks. Final hook-up of ordnance circuitry will be conducted during prelaunch countdown operations.

(11) Complete SRM Assembly

Installation of raceway covers, the nose fairings, and attachment structures will complete the assembly operation. The assembled

III.B. Production Program (cont)

and checked out SRM is then ready for final inspection and orbiter integration operations.

The procedures described above will proceed concurrently on two SRMs. It is recognized as including just the major steps necessary for defining manpower and AGE requirements and to arrive at a realistic time-line.

An illustration of the proposed sequence of operations through the KSC facility is shown in Figure III-14.

c. Development of SRM Operational Time-Line

The operational analysis described in the preceding section was expanded in more detail (Appendix C), and the time required to complete each task was estimated. Operations that could be conducted concurrently were defined.

The projected time to fully assemble, check-out and prepare two SRMs for mating with the orbiter tankage is 134 hr. Assuming 85% operating efficiency, 160 hr or a 2-shift operation for 10 working days would be required to achieve ready-status of the booster stage for orbiter integration. This schedule also assumes two complete work crews on each shift.

The time-line (Figure III-15) is insensitive to segment size or weight but dependent on the number of center segments. Approximately one shift per segment would be added (or subtracted) for different motor configurations.

Deletion of the TVC system would result in a reduction of about 12 hr in the total stage preparation time.

III.B. Production Program (cont)

The two-crew, two-shift operation using a single high-bay area of the VAB can support a launch rate of 17 flights per year. Four high bays (or equivalent) are needed for a 60-flight per year traffic model.

d. Man-Power Requirements

Manning levels at KSC to support the SRM booster stage assembly, check-out, inspection, orbiter integration and mission support operations were established. The baseline traffic model and the operational time-line provided the input necessary to define the personnel requirements. Requirements for each operational function, supervision, supporting services, safety, documentation, government and orbiter contractor coordination, AGE maintenance and base management were considered.

Further, the following ground rules and assumptions were made:

(1) Aerojet Responsibilities

(a) Receiving inspection of SRMs and stage subsystems

(b) SRM assembly and check-out

(c) Technical assistance and surveillance of orbiter mating combined systems checks and launch operations

(d) Flight performance analysis (booster systems)

(e) Maintenance of SRM peculiar AGE

(f) Management of bonded storage areas

III.B. Production Program (cont)

(2) NASA Responsibilities

(a) Transportation and handling of segments

(b) Crane operators at storage site and VAB

(c) Maintenance of facilities and none-SRM AGE

Crew size was incrementally increased in accordance with the yearly launch rate. The manning level for the first full year of flight operations (1978, six launches) consists of 51 people of the following classifications:

Mechanical and electrical technicians	12
Inspectors	3
Engineers	13
Supervision, administration	9
Support	14
Total	51

The maximum KSC-based crew size reaches 147 in 1985 when the peak launch rate occurs. Additional specialists and engineering support is available at the A-DD facility in Homestead, Florida, if needed on a temporary basis.

e. Aerospace Ground Equipment (AGE) Requirements

The type and quantity of all AGE required to conduct motor and component handling assembly, inspection, and check-out operations was defined using the operational analysis and the baseline traffic model for a parallel burn orbiter. The technical requirement of each article and the

III.B. Production Program (cont)

recommended design was established to the extent necessary to permit preparation of cost estimates.

The baseline motor configuration (two center segments, no TVC) was considered and cost deltas determined for a motor with three center segments and a TVC system. The study assumed motor arrival by barge, with segments vertical, forward end up. No major rail or wheeled transporters were included in the cost, as it is understood that the NASA owns such items which may be modified for use and would be available as GFE.

Cost estimates were generally based on the actual cost of similar items used on other programs (Titan, Minuteman, or 260-in.-dia Motor Programs with adjustments for size and weight difference where applicable. AGE total quantity requirements are based on a turn-around of major items (storage pallets and rings) every 10 weeks at the maximum delivery rate of ten SRMs per month (to support 60 flights/year).

A listing of the total AGE requirements appears in Figure III-16.

f. KSC Facility Requirements

No KSC facility costs have been included in the program cost data. The facilities have been identified, however, and requirements defined.

The only major facility item, accountable only to booster-assigned costs, would be a new SRM storage and inspection building, (MSIB). Ideally, this facility would be located within 3000 ft of the VAB and have the following capabilities or features.

III.B. Production Program (cont)

(1) Be adjacent to the barge terminal, or slip, with an overhead bridge-crane (250 ton capacity) capable of off-loading the SRM segments and placing them in assigned vertical storage positions. Minimum crane hook height should be 40 ft.

(2) Have an environmental control system capable of maintaining specified temperature and humidity levels for about 40,000 sq ft of enclosed area.

(3) Provide storage space for six complete SRMs assuming a three center segment configuration.

(4) Provide a bonded storage area for components and subsystems.

(5) Provide an area for inspection of segments and stage articles.

(6) Incorporate all normal utility, fire-protection, and communication services.

(7) Have rail tracks in center aisle, extending to the transfer aisle of VAB.

Additional facility modifications required would include extension of the present canal (now terminated adjacent to the VAB) to the storage site, construction of the barge turning-basin and docking facilities, and the above-mentioned rail system.

Modifications that may be necessary to the crawler-tractor, LUT, or launch complex have not been studied. SRM operations in the VAB should not, by themselves, require any alteration to that facility.

III. Program (cont)

C. PROGRAM COSTS

1. Costing Approach

Because large solid rocket technology is within the current state-of-the-art, having been demonstrated in 120-, 156-, and 260-in.dia motors, it was possible in this study to adopt a costing approach similar to that used in a proposal for procurement purposes. Upon establishment of a Baseline Program definition, a program plan and component drawings were prepared in sufficient detail to enable realistic cost estimates to be prepared.

Subcontractor and supplier estimates were obtained on a bid basis for all major materials and items of hardware. To assure maximum validity, only experienced and qualified subcontractors who, in most cases, had actually produced components for 120-, 156-, or 260-in.-dia motors, were solicited for quotations. The individual estimates for a specific item were compared one to another and cross-checked against an internally prepared engineering cost estimate. An analysis, summarized later in this section, confirmed that, when normalized for quantity and design differences, the quotations for major components were, indeed, consistent with prior experience.

Similar reliance on actual experience was used in the preparation of in-house estimates for engineering, manufacturing, and quality control, as well as for support functions, including indirect or overhead costs. Detail manufacturing and quality control plans were prepared depicting the processing and assembly sequence from which the manpower, tooling, and facility requirements were established.

Estimates of in-plant manufacturing labor were prepared by individuals responsible for similar or identical work performed previously at

III.C. Program Costs (cont)

the Dade County Plant and currently at the Sacramento Facility. Direct labor hours were determined for each detail element of the process sequence, based on experience with identical or similar operations, using identical or similar tooling and equipment in identical or similar facilities. Cross checks of these detail estimates were made against existing current Industrial Engineering Standards for identical or similar operations.

Labor for support functions such as supervision, production control, and manufacturing engineering were based on manloading of similar or identical facilities and were compared for reasonableness with actual costs incurred on similar programs.

Manloading of the A-DD Facility was planned on a three-shift-per day seven-day week as required to obtain maximum utilization of facilities in meeting program schedules. Administrative and maintenance functions were provided as an overhead factor consistent with experience at both the Sacramento and A-DD facilities and the scope of the planned program.

Cost estimating of facilities was accomplished by breaking down the building layouts of the facility plan into individual elements of construction. Each element of construction was then costed using accepted factors for construction in the Dade County, Florida, area. Subcontractor bids and/or historical price data was used for all items of major equipment to be installed.

Tooling estimates were prepared by comparing the cost of each individual tooling item of the tooling plan to the actual cost of similar tools of both larger and smaller size. Adjustments to cost were applied for identifiable differences in complexity, material of construction, etc. Subcontractor bids were obtained for major, complex tooling items.

III.C. Program Costs (cont)

2. Ground Rules

Costs presented in this report are based on the following ground rules and assumptions.

a. All costs are in 1970 dollars (no escalation)

b. Aerojet fee is not included

c. KSC facilities are not included

d. 440 operational flight mission model

e. Baseline Program

156-in.-dia SRM with 1,000,000 lb propellant
Parallel configuration
Expendable hardware
No thrust vector control
No thrust neutralization

Separate costs are presented for the following:

a. Thrust vector control and thrust neutralization subsystem options.

b. 156-in.-dia SRM booster with 1,250,000 lb propellant.

c. Recoverable booster

III.C. Program Costs (cont)

3. Baseline Program Costs

Detailed cost breakdowns of the Solid Rocket Motor and the Stage Components for the Baseline Program are presented per NASA format in Figures III-17 and III-18, respectively, and summarized below:

SRM Booster with 1,000,000 lb Propellant

($ in millions)	Nonrecurring		Recurring	Total
	DDT&E	Facilities		
Baseline Program				
SRM	76.4	112.4	1,307.5	1,496.3
Stage	21.1	-	343.1	364.2
Total (Baseline)	97.5	112.4	1,650.6	1,860.5

4. Program Options

Thrust Vector Control (TVC) and Thrust Neutralization (TN) have been costed separately and are presented as additive options:

($ in millions)	Nonrecurring		Recurring	Total
	DDT&E	Facilities		
Options				
TVC	11.4	-	140.6	152.0
TN	2.3	-	46.9	49.2
Total (Options)	13.7	-	187.5	201.2
Total Program with Options	111.2	112.4	1,838.1	2,061.7

III.C. Program Costs (cont)

a. SRM Booster with 1,250,000 lb Propellant

In addition to the baseline motor size (1,000,000 lb propellant) selected by Aerojet for this study, NASA requested that costs be developed for a 156-in.-dia SRM booster with 1,250,000 lb propellant. Because time constraints did not permit an in-depth investigation of various motor sizes, a comparative analysis approach was adopted in which the effect of size increase was evaluated for each component of the booster. In addition to factoring processing labor and materials for the greater size, the effect on handling, shipping, tooling and facilities was taken into consideration. The results of this analysis are reflected in the detail breakdown for the motor and stage components shown in Figures III-19 and III-20, respectively. These costs are summarized below:

SRM Booster with 1,250,000 lb Propellant

($ in millions)	Nonrecurring			
	DDT&E	Facilities	Recurring	Total
Baseline Program				
SRM	86.8	129.3	1,554.5	1,770.6
Stage	22.5	-	375.5	398.0
Total (Baseline)	109.3	129.3	1,930.0	2,168.6
Options ( )				
TVC	14.5	-	159.2	173.7
TN	2.4	-	49.2	51.6
Total (Options)	16.9	-	208.4	225.3
Total with Options	126.2	129.3	2,138.4	2,393.9

C4

III.C. Program Costs (cont)

b. Recoverable Booster

A limited cost analysis was also performed of a program based on recovery and reuse of booster hardware. The reuse factors for the various motor and stage components and the rationale in support thereof are presented in this report. The delta cost effect of the recoverable approach on each affected component and subsystem is presented in Figure III-21. It is estimated that the recovery program, despite higher nonrecurring costs, will pay off after 50 flights. For the total 440 flight mission mode, a reduction of approximately 30% from the expendable program cost was realized, as shown in Figure III-22. The following is a summary of the recovery program costs (including Thrust Vector Control and Thrust Neutralization options) for both 1,000,000 and the 1,250,000 lb propellant boosters:

($ in millions)	Nonrecurring			
	DDT&E	Facilities	Recurring	Total
1.0 million lb Booster	212.6	98.4	1,122.0	1,433.0
1.25 million lb Booster	232.6	108.9	1,293.4	1,634.9

Figure III-22 shows graphically the effect of the recovery approach on the relative cost of SRM booster components.

5. Recurring Cost per Launch

The following table shows the average recurring cost per launch for both the expendable booster and the recoverable booster and for the motor sizes and configurations specified (costs include TVC and TN options):

III.C. Program Costs (cont)

($ in millions)	Parallel Configuration	Series Configuration
Expendable Booster		
SRM with 1.0 million lb Propellant	4.2	6.2
SRM with 1.25 million lb Propellant	4.9	7.3
Recoverable Booster		
SRM with 1.0 million lb Propellant	2.6	3.8
SRM with 1.25 million lb Propellant	2.9	4.4

The effect of launch rate on launch cost is shown in Figure III-23. The effect of propellant weight on launch cost is shown in Figure III-24.

6. Related Cost Experience

Comparative cost data for various motor components for the current 156-in.-dia SRM cost projection and prior large solid rocket motor experience is presented in Figure III-25. A brief analysis of these items, which represent over 70% of the total recurring costs of the Space Shuttle Booster Program, is presented below:

a. Case Fabrication

The higher 260-in.-dia SRM case cost/lb is attributable to the limited number of units produced (2) and to the higher cost material (18% nickel maraging steel vs D6aC steel). When adjusted for these two factors, the cost is consistent with the projected 156-in.-dia SRM case cost.

The actual cost of the 120-in.-dia SRM segmented case (manufactured of D6aC steel) has been normalized to 890 units to make it directly comparable to the 156-in.-dia SRM cost.

III.C. Program Costs (cont)

b. Insulation

The higher 260-in.-dia SRM insulation cost is again attributable to the limited number of units produced.

The 120-in.-dia SRM insulation cost, although normalized to 890 units, reflects a more complicated design, including the use of five-segmented-end restrictors as compared with one restrictor on the 156-in.-dia SRM.

c. Nozzle

The comparison with the 260-in.-dia SRM is made on the basis of fixed nozzles (without TVC) with the difference in cost/lb explained in terms of quantity (2 vs 890).

d. Propellant Material

The cost for 156-in.-dia SRM propellant materials is applicable to HTPB or PBAN propellants. Taking into consideration the vastly greater quantity of material, the cost is compatible with the 260-in.-dia SRM experience.

e. Propellant Processing

The cost per pound for propellant processing is approximately the same for the 260- and 156-in.-dia SRMs. Since the pace of this operation is to a great extent machine controlled, the quantity effect of the 156-in.-dia SRM shuttle program is negligible. The slightly higher cost shown for the 156-in.-dia SRM is due to additional setups in casting segments as compared to a unitized 260-in.-dia SRM.

III.C. Program Costs (cont)

f. Learning Curve Slope

Because the propellant processing operations are machine controlled, the greatest learning potential is in the area of assembly operations. A more conservative (95%) learning curve slope was projected for the 156-in.-dia SRM than experienced on the Minuteman program because the Minuteman assembly operations are more complex and, thus, more susceptible to learning.

g. Stage Components

The \$18/lb average cost for 440 units used in this study is compatible with the NASA quoted figure of \$29/lb first unit cost for the SRM stage components on the Titan IIIC program.

7. Time-Phased Studies

As shown in Figure III-26, the funding requirement for the baseline program reflects a gradual increase from \$21 million the first year to a peak of \$222 million in 1983. Time-phased funding requirements broken down by elements of nonrecurring and recurring costs per NASA format are presented in Figures III-27 and III-28.

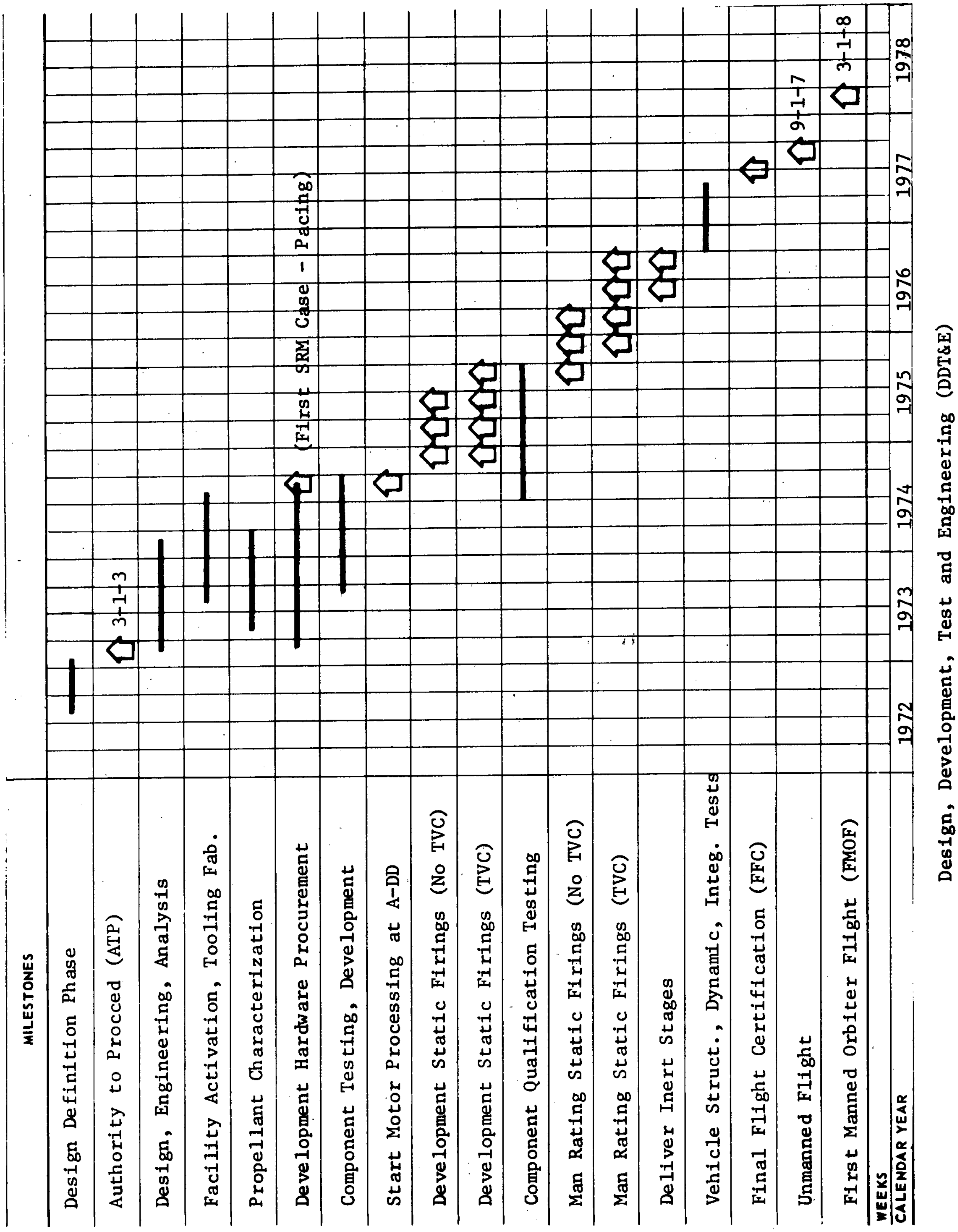

MILESTONES
Design Definition Phase
Authority to Procced (ATP)
Design, Engineering, Analysis
Facility Activation, Tooling Fab.
Propellant Characterization
Development Hardware Procurement
Component Testing, Development
Start Motor Processing at A-DD
Development Static Firings (No TVC)
Development Static Firings (TVC)
Component Qualification Testing
Man Rating Static Firings (No TVC)
Man Rating Static Firings (TVC)
Deliver Inert Stages
Vehicle Struct., Dynamic, Integ. Tests
Final Flight Certification (FFC)
Unmanned Flight
First Manned Orbiter Flight (FMOF)
WEEKS
CALENDAR YEAR
1972
1973
1974
1975
1976
1977
1978
3-1-3
(First SRM Case - Pacing)
9-1-7
3-1-8
Design, Development, Test and Engineering (DDT&E)

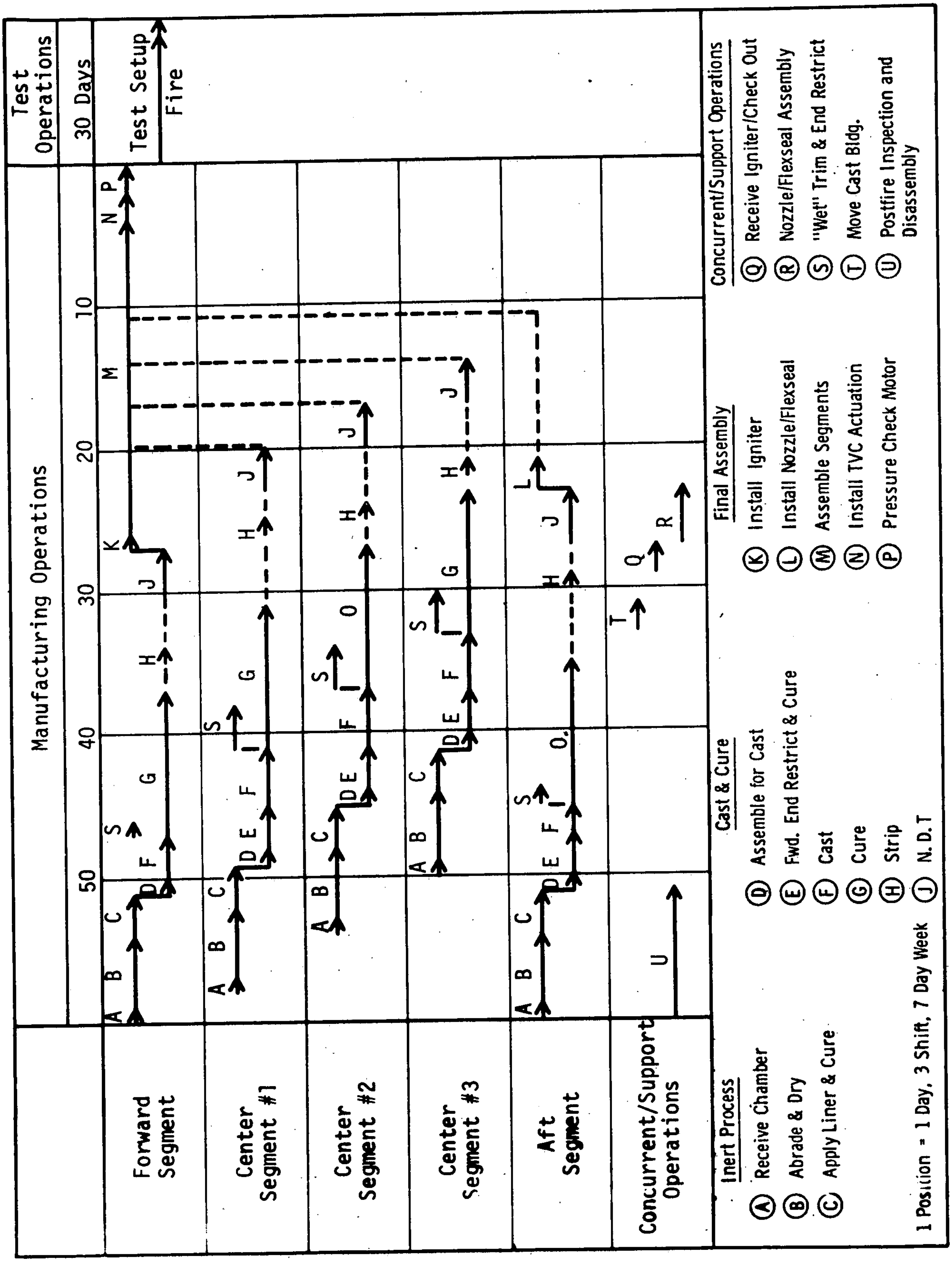
Figure III-1

Component/Subsystem Design Task	Supporting Analyses: Structural	Thermal	Other
Motor			
Case	X		
Insulation		X	
Grain	X		Dynamic/Ballistic
Igniter	X	X	Ballistic
Nozzle	X	X	Aerodynamic
(TN) including Stacks*	X	X	Aerodynamic
(TVC) Flexseal only*	X	X	Performance
Stage			
(TVC Actuation) Heat Shield*	X	X	Performance
Base Structure and Attachments	X		
Nose Fairing and Attachments	X		
Destruct	X		E.M.I.
Instrumentation/Electrical	X		E.M.I.

*Program options

Design Task Summary

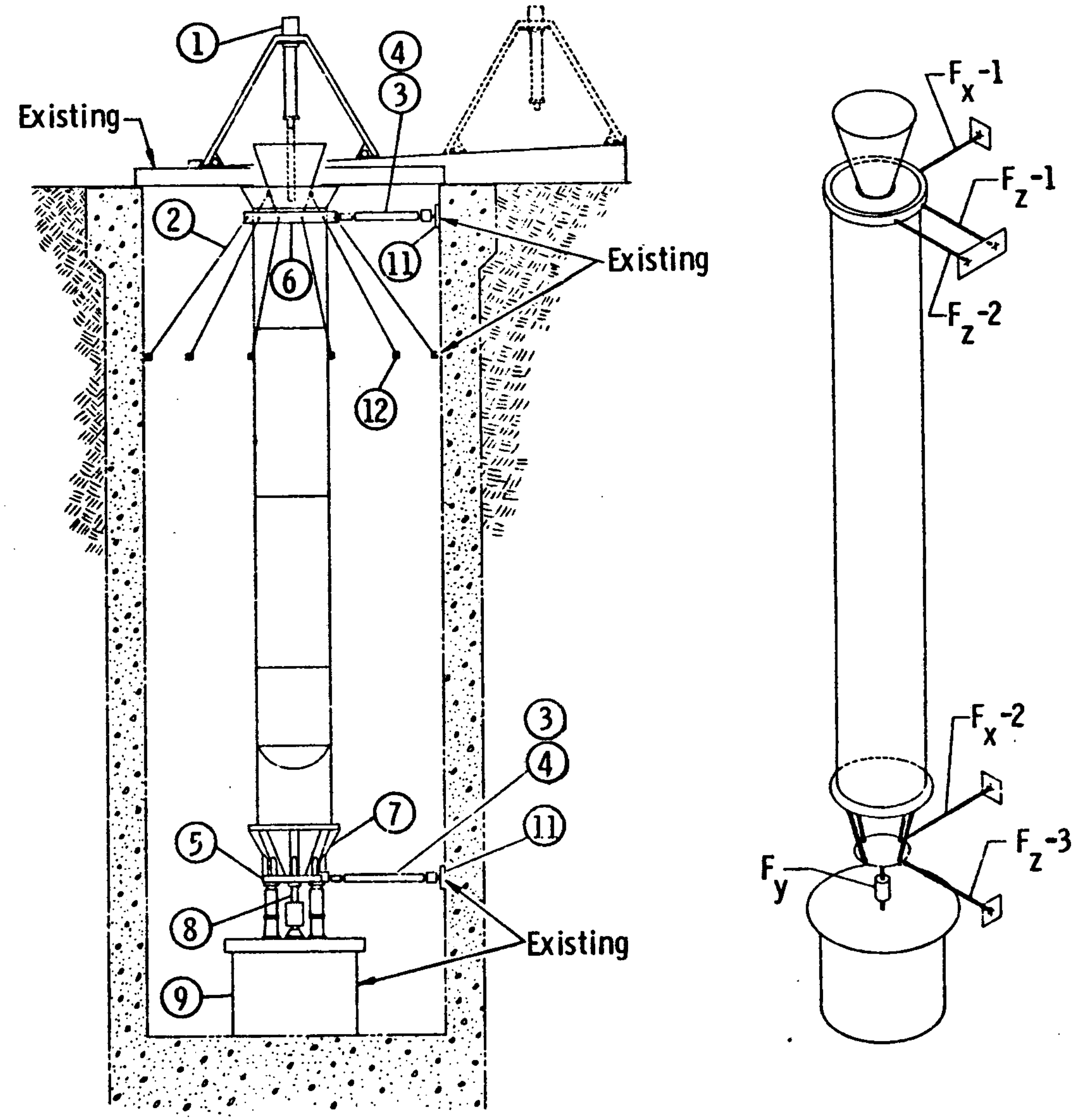
Figure III-2



Assembly Sequence Chart

Figure III-3

1. Motor Quench System
2. Flight Retention
3. Stabilize & Side Force Take Out
4. Side Force Calibration System
5. Fwd Firing Ring & Motor Adapter
6. Aft Firing Ring
7. Thrust Tripod
8. Rod Flexure
9. Thrust Adapter (Modify)
10. Thrust Termination Duct
11. Mounting Plates (Modify-Relocate)
12. Mounting Plates (Modify)



156-in.-dia Development Motor Test Layout

Figure III-4

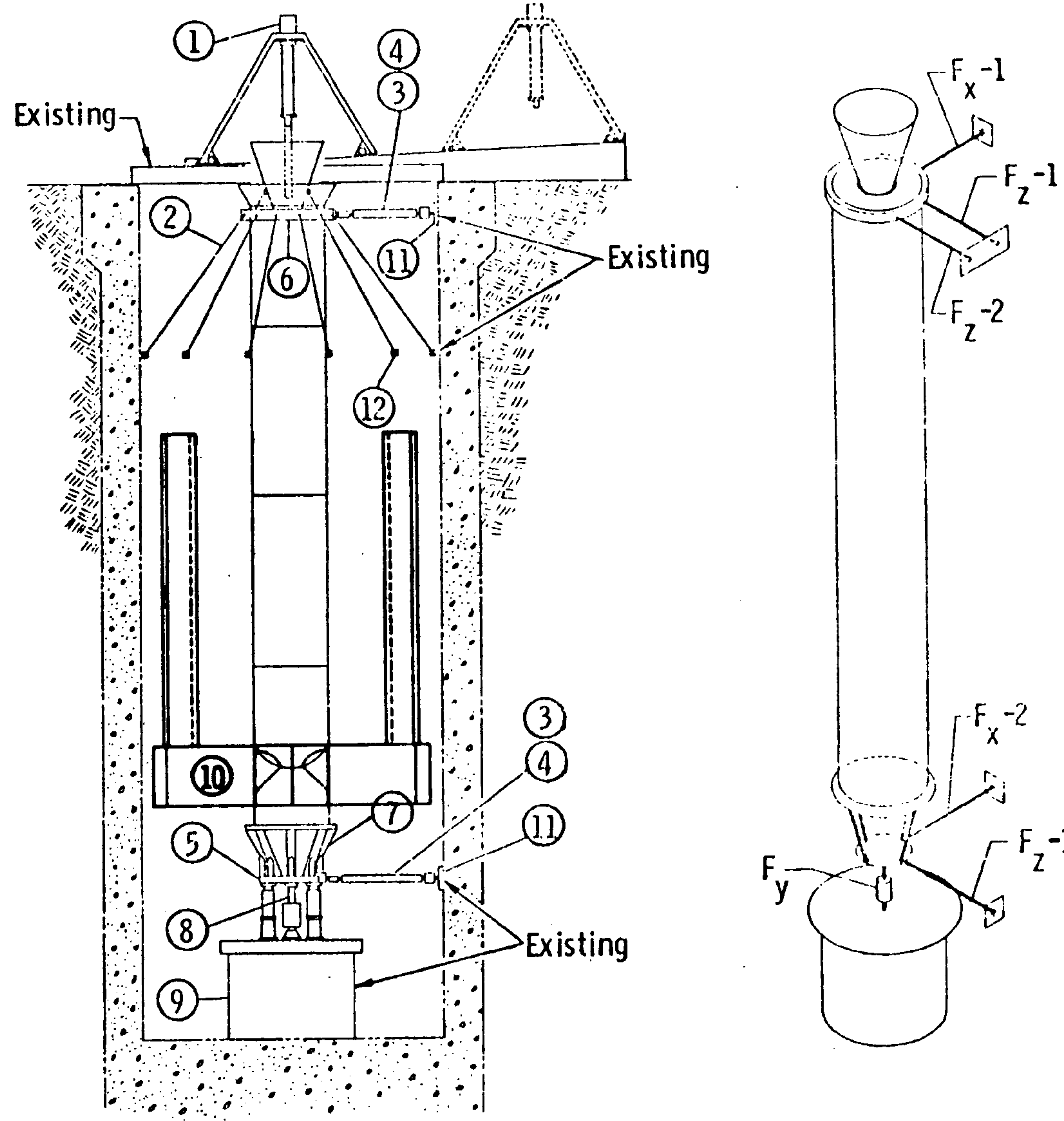
Test	Configuration	Test Objectives: Without TVC	Test Objectives: With TVC*
1	Flight weight case and nozzle Forward head igniter Test weight aft skirt extension Development phase TVC complete	Define ignition transient Verify ballistic performance Confirm material performance Confirm acceptability of motor design and manufacturing processess Acquire data on dynamic, thermal and acoustic environment on and around motor	Verify flexseal design and performance Obtain maximum engineering data on TVC system performance Confirm deflection/side force/torque relationships Monitor environmental exposure of components
2	Same as Test 1, plus Flight safety system sensors Ordnance devices, less shaped charges Fully developed TVC system	Establish reproducibility of motor and component performance Demonstrate operation of ordnance systems (less shaped-charges) Evaluate flight safety sensor response to simulated malfunction	Obtain maximum engineering data on TVC system performance Establish reproducibility of TVC system performance Verify TVC system meets all specified requirements
3	Frozen design Qualified ordnance Qualified TVC system Flight weight aft support section, heat shield, and forward structures	Verify acceptability of any design changes resulting from first test Confirm all-up motor is ready for manrating testing	Maximum performance duty cycle Verify acceptability of end-to-end TVC system using qualified components
4	Same as Test 3 TN shaped charge (with TVC)	Not applicable (only 3 test firings required)	Establish TVC response to flight profile duty cycle Demonstrate thrust neutralization Confirm all-up motor is ready for manrating testing

* In addition to baseline motor objectives.

Development Motor Tests

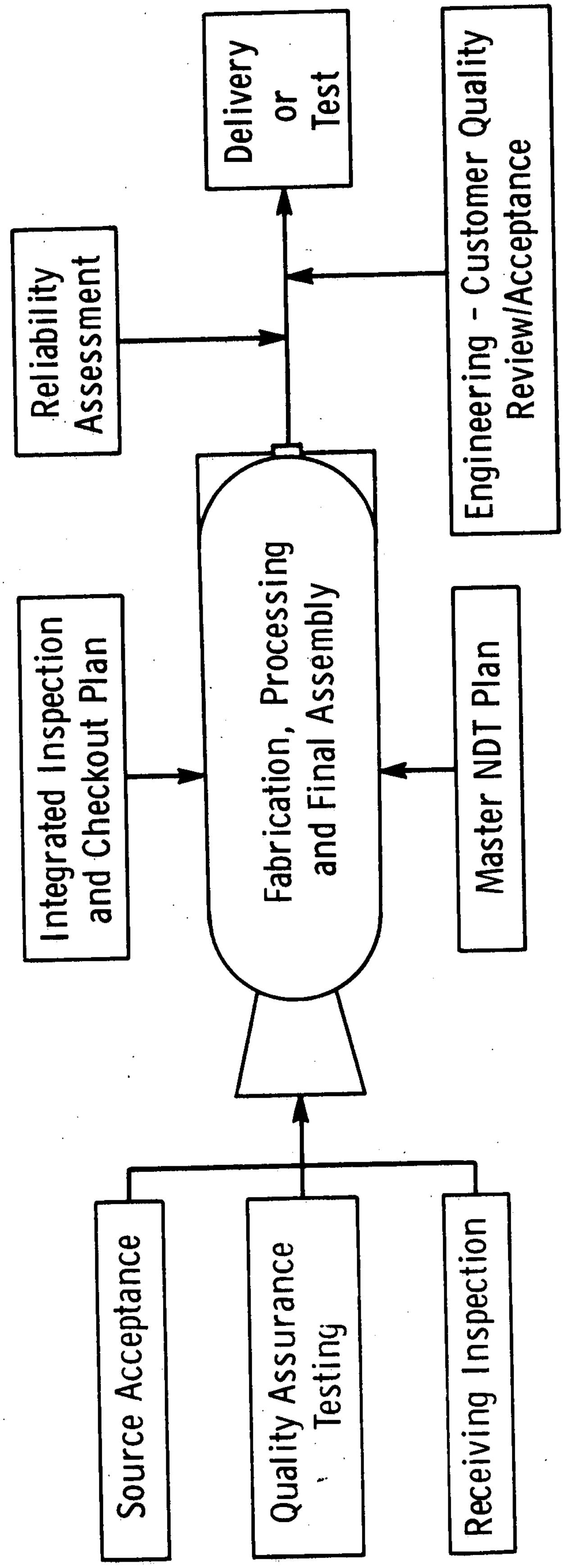
Figure III-5

1. Motor Quench System
2. Flight Retention
3. Stabilize & Side Force Take Out
4. Side Force Calibration System
5. Fwd Firing Ring & Motor Adapter
6. Aft Firing Ring
7. Thrust Tripod
8. Rod Flexure
9. Thrust Adapter (Modify)
10. Thrust Termination Duct
11. Mounting Plates (Modify-Relocate)
12. Mounting Plates (Modify)



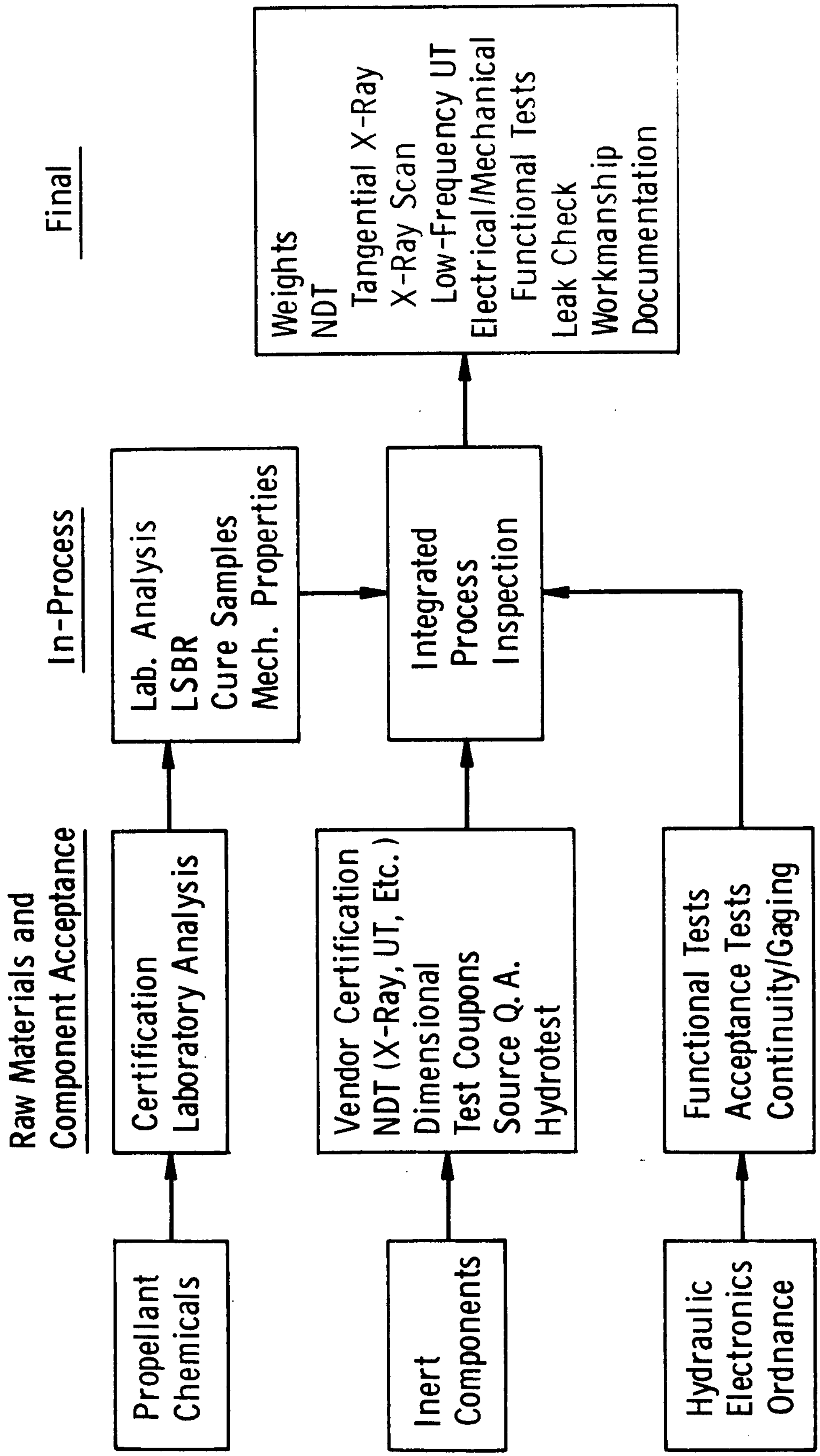
156-in.-dia Development Motor Test Layout

Figure III-6



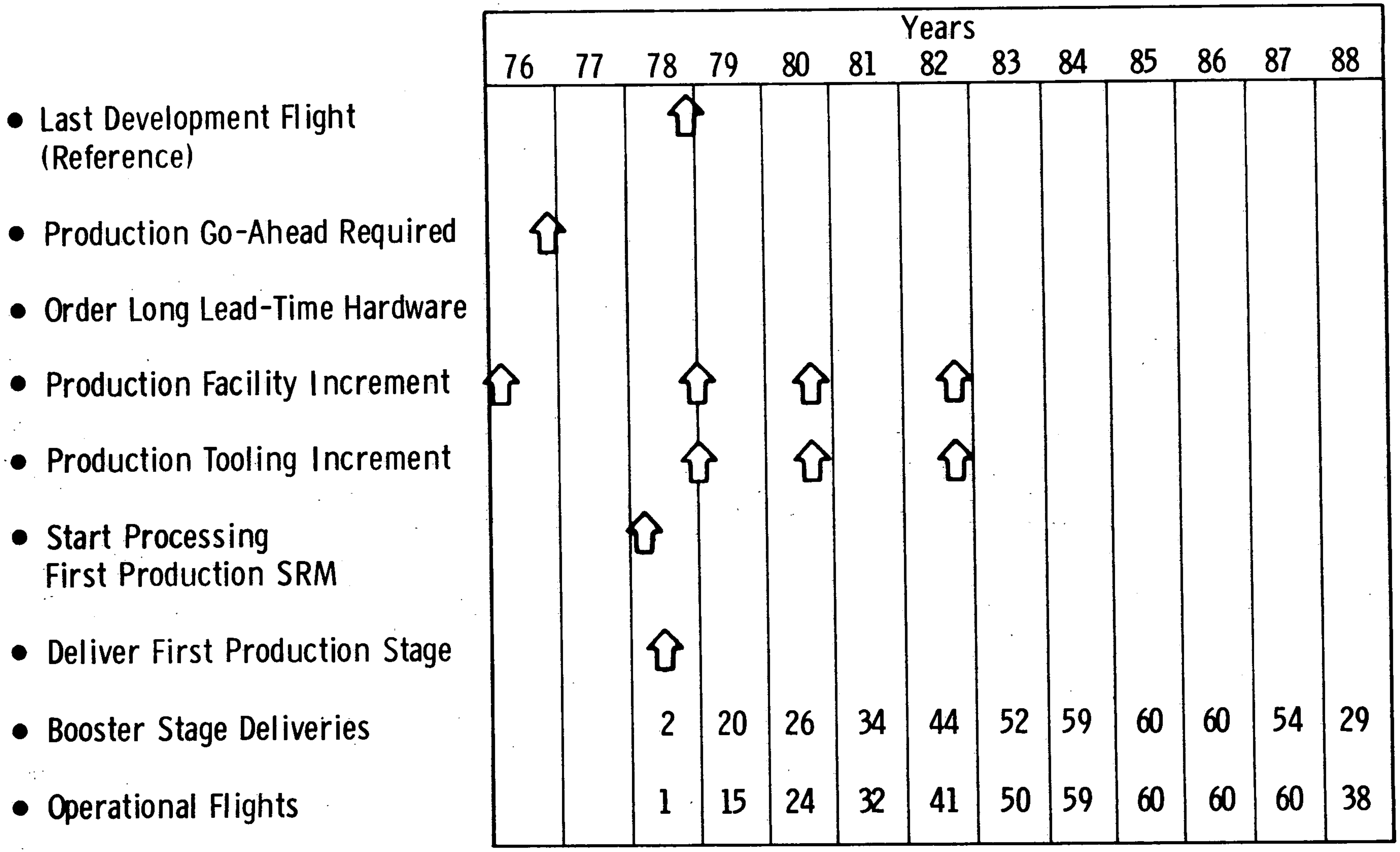
Quality Assurance Plan Requirements

Figure III-7



Quality Assurance Flow Plan

Figure III-8



Production Program - 440 Flights

Figure III-9

Motor Processing Sequence (Production)

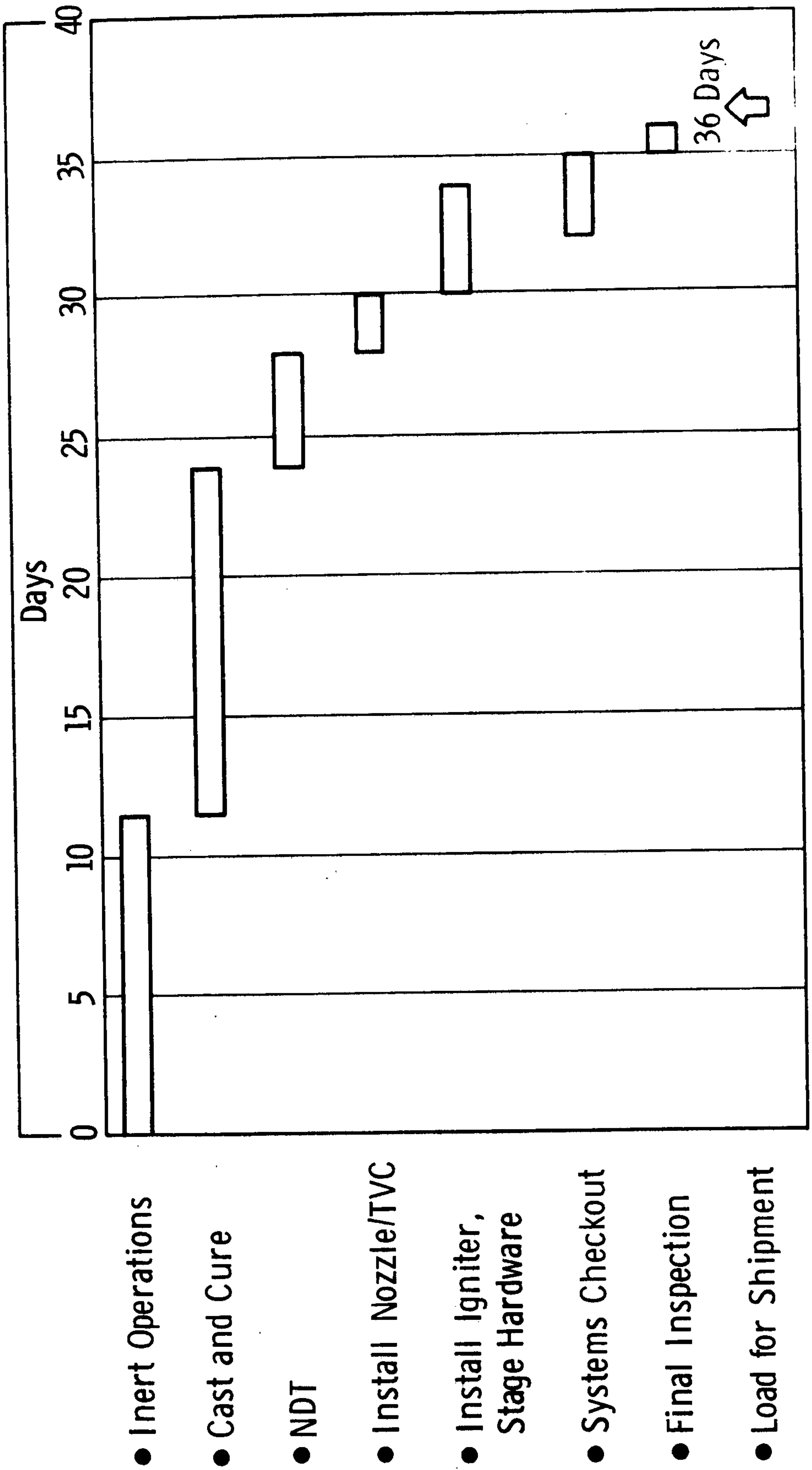
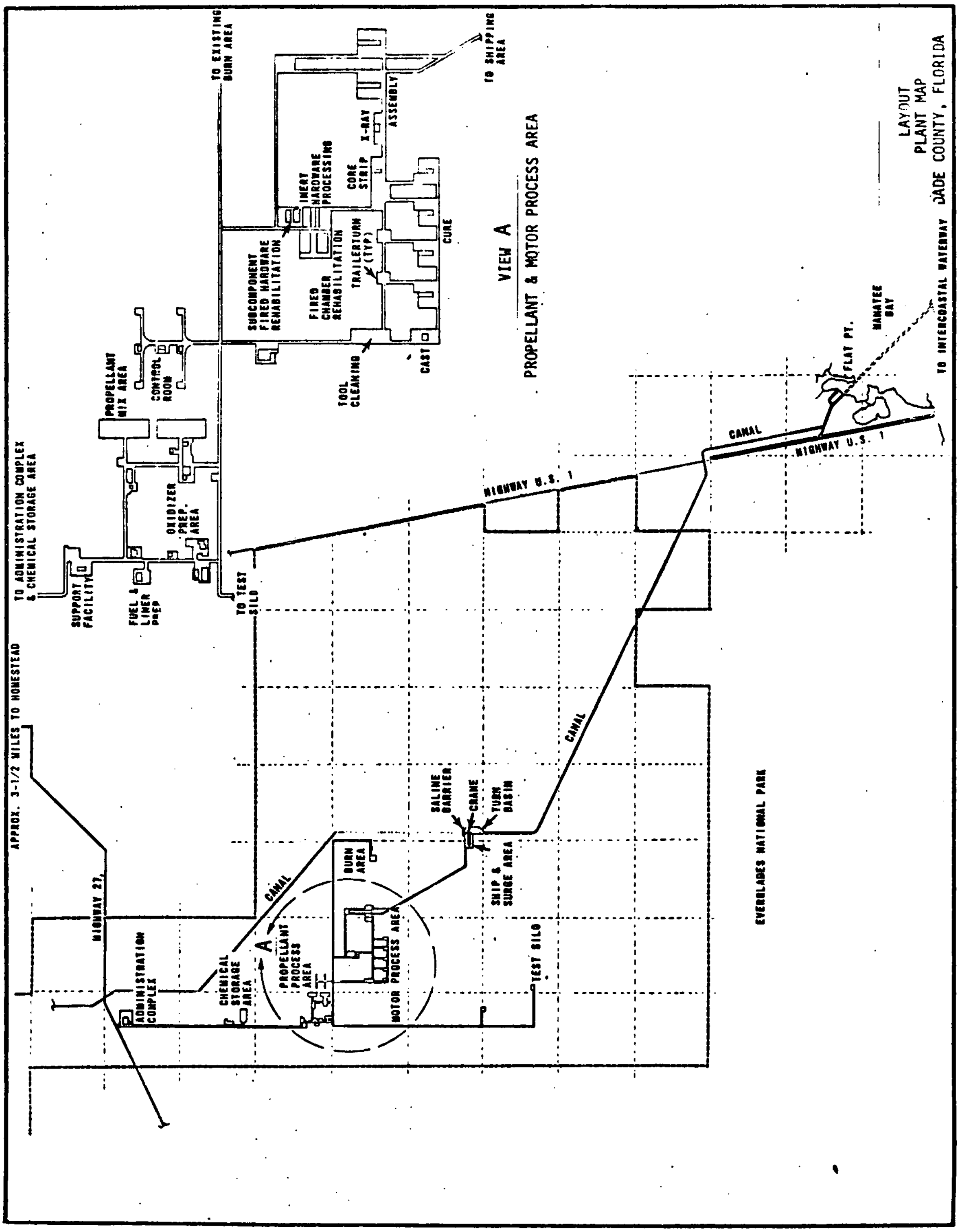


Figure III-10

	New Facilities Required	Activation Date	Capacity Motor/yr
Development	None	June 1974	4 (Processing) 36 (Propellant)
Production	Inert Processing (2)	January 1976/August 1982	48/120
	Core Preparation and Strip	January 1976	120
	Cast and Cure (3)	January 1976/August 1980/ August 1982	48/84/120
	Mix Station (4)	January 1979/July 1982	84/120
	Premix Preparation	January 1979	120
	Final Assembly (2)	January 1976/August 1982	48/120
	Oxidizer Processing	August 1982	120
	Shipping and Storage	January 1976	120

Motor Processing Facilities

Figure III-11



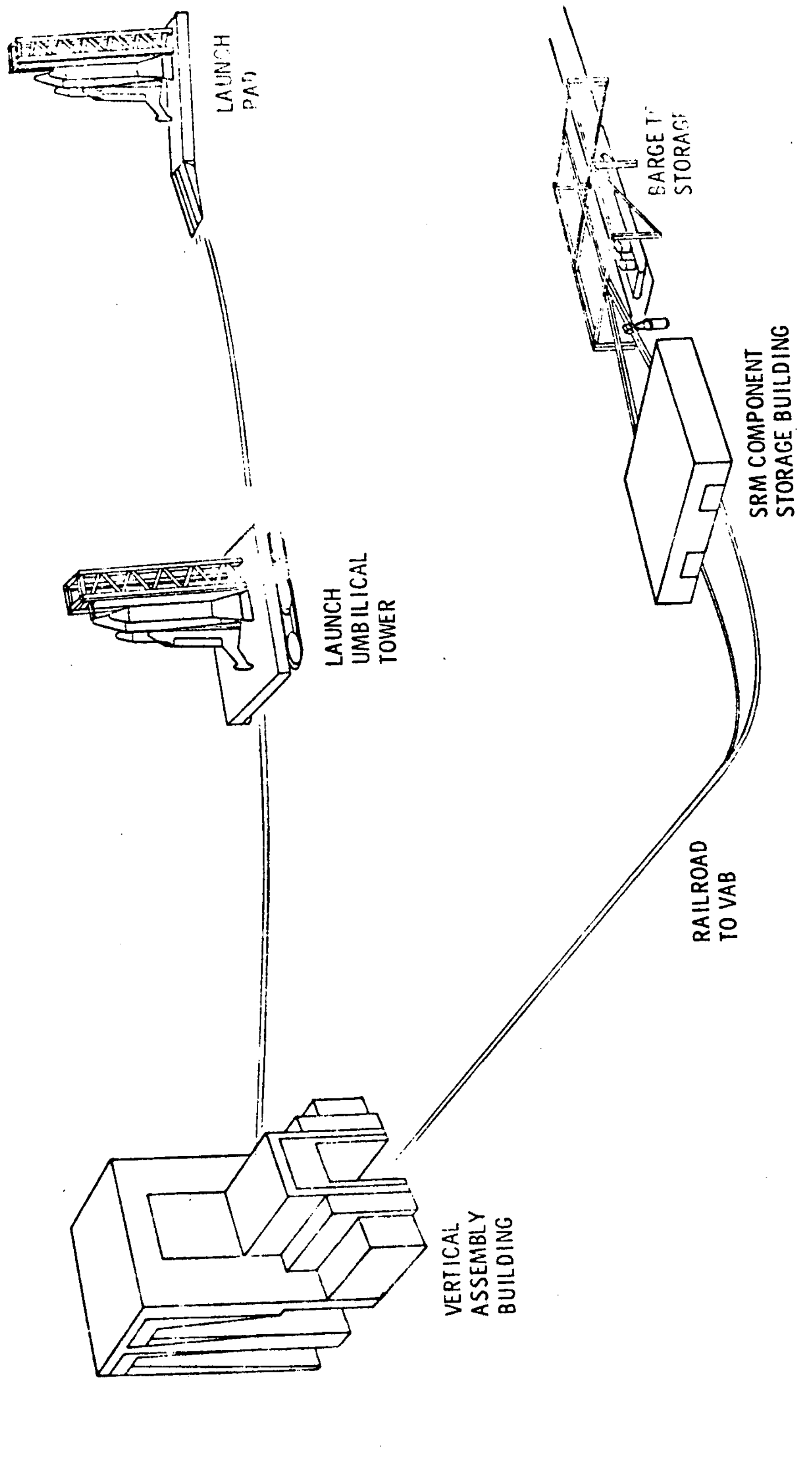
Layout Plant Map Dade County, Florida

Figure III-12

Element	From	Mode
● Insulated Segments	● Fabricator to A-DD	● Rail
● Nozzle	● Supplier to A-DD	● Truck
● Aft Exit Cone	● Supplier to KSC	● Truck or Rail
● Propellant Chemicals	● Suppliers to A-DD	● Truck and Rail
● Stage Support and Fairings	● Fabricator to KSC	● Rail or Barge
● Loaded Segments	● A-DD to KSC	● Barge

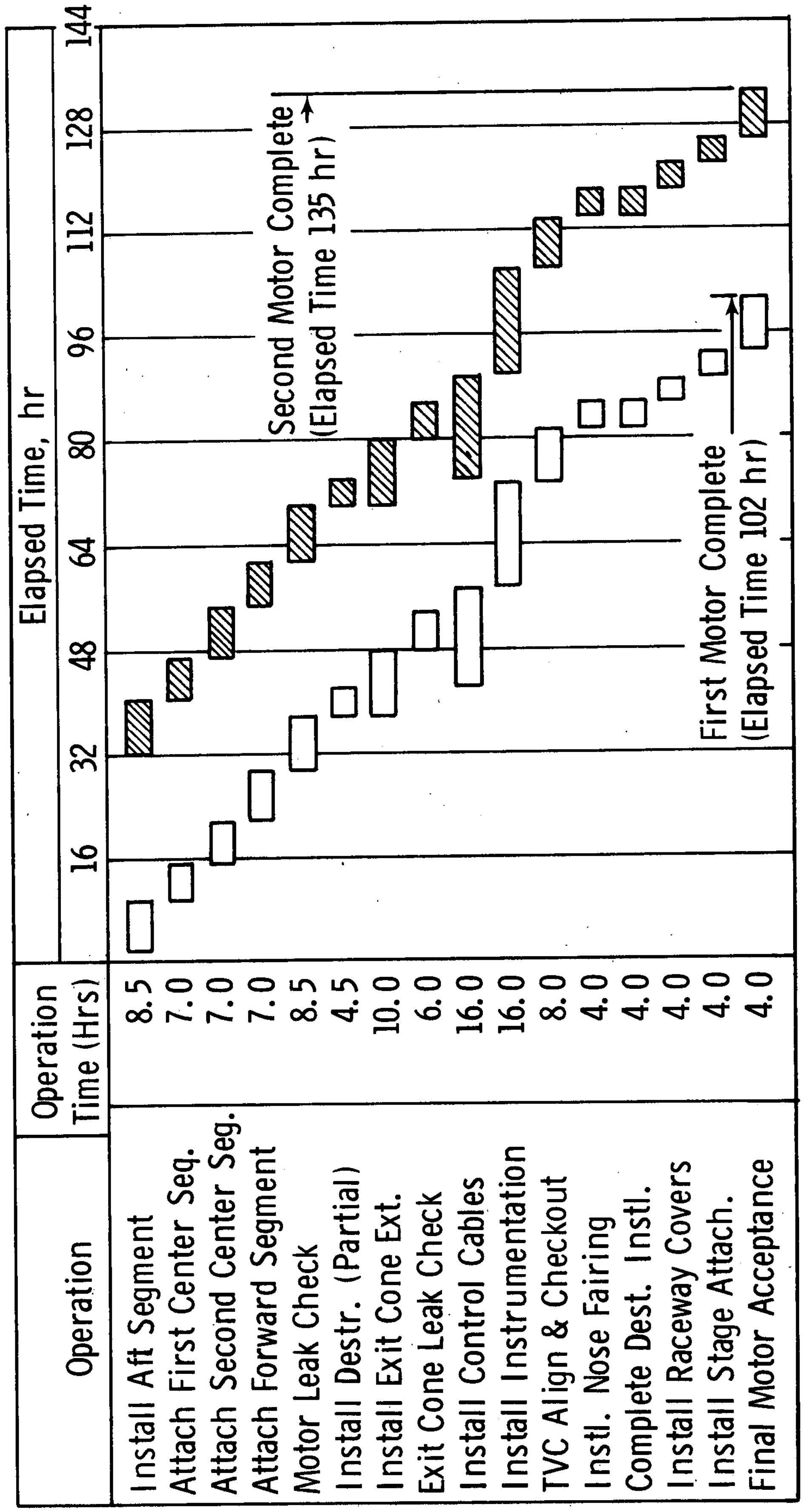
Transportation Plan - Major Items

Figure III-13



Facility Utilization

Figure III-14



Launch Site Operations Timeline

Figure III-15

Nomenclature	Qty	Delivery Schedule 76	77	78	79	80	81	82	Function
Pallet-shipping and storage aft segment	40	7		6	5	6	7	9	Shipping and storage
Pallet-shipping and storage forward and center	120	21		18	15	18	21	27	Shipping and storage
Handling end ring, forward segment	8	4		2	2				Handling and assembly
Handling end ring, center and aft segment	24	12		8	4				Handling and assembly
Cover, environmental	120	21		18	15	18	21	27	Shipping and storage
Plug, nozzle throat	40	7		6	5	6	7	9	Shipping and storage
Transport dolly, rail, segment	2	2							KSC transport (GFP)
Hoisting sling, beam type, segment	5	3		1	1				Handling and assembly
Fixture, exit cone installation and removal	4	2		1	1				Assembly and checkout
Handling sling, nozzle exit cone	4	2		1	1				Assembly and checkout
Handling cover, motor leak check	4	2		1	1				Assembly and checkout
Fixture, leak check, exit cone	4	2		1	1				Assembly and checkout
Test set, leakage	4	2		1	1				Assembly and checkout
Test set, electrical	4	2		1	1				Assembly and checkout
Test set, ordnance	4	2		1	1				Receiving inspection, assembly and checkout
Test set, TVC	4	2		1	1				Assembly and checkout
Kit, base heat installation and repair	4	2		1	1				Assembly and checkout
Kit, pin and band, installation and removal	8	4		2	2				Assembly and checkout
Kit, ordnance installation and removal	8	4		2	2				Assembly and checkout
Fixture, nozzle alignment	4	2		1	1				Assembly and checkout
Sling, igniter installation and removal	2	2							Maintenance

Support Equipment Requirements

Figure III-16

$ in millions
SRM with 1,000,000 lb propellant
Parallel configuration
Without TVC or TN

	DDT&E						PRODUCTION	OPERATIONS	TOTAL PROGRAM
	ENGRG DESIGN & DEV (EDD)	TOOLING (TOOL)	GROUND TEST HDWR (GTH)	FLIGHT TEST HDWR (FTH)	OTHER (OTH)	TOTAL (TOT)			
3.3.2 SOLID ROCKET MOTORS									
3.3.2.1 Program Management						.628	.825		1.453
3.3.2.2 Systems Engineering						.854	.678		1.532
3.3.2.3 SRM's									
2.3.1 Structures									
Case	1.653	9.207	4.651	8.378		23.889	577.278		601.167
Insulation	1.465	2.624	.926	1.426		6.341	77.827		84.168
Nozzle (w/o Flex Seal)	1.515	3.206	2.090	3.578		10.389	255.772		266.161
Igniter	1.396	.213	.326	.137		2.072	7.038		9.110
Propellant	1.973		1.958	3.672		7.603	263.981		271.584
2.3.2 Motor Processing & Subassembly	2.073	12.038	2.886	5.514		22.511	101.107		123.618
2.3.3 Ground Tests		.594	.845			1.439			1.439
3.3.2.4 Facilities			5.866	21.748		27.614	84.793		112.407
3.3.2.5 Systems Support									
2.5.1 Support Equipment & Spares	.168					.168	5.710	4.800	10.678
2.5.2 Flight Test Support				.212		.212		2.609	2.821
2.5.3 Operations Support				.254		.254		6.052	6.306
3.3.2.6 Shipping				.056		.056	3.809		3.865
TOTAL	10.243	27.882	19.448	44.975		104.030	1,378.818	13.461	1,496.309

SRM Cost Estimate

Figure III-17

$ in millions SRM with 1,000,000 lb propellant Parallel configuration Without TVC or TN	DDT&E ENGRG DESIGN & DEV (EDD)	TOOLING (TOOL)	GROUND TEST HDWR (GTH)	FLIGHT TEST HDWR (FTH)	OTHER (OTH)	TOTAL (TOT)	PRODUCTION	OPERATIONS	TOTAL PROGRAM
3.3.1 STAGE									
3.3.1.1 Program Management									
3.3.1.2 System Engineering						.491	.491		.982
3.3.1.3 Stage						642	.451		1.093
1.3.1 Structures									
Attach Structures	1.223	.255		.612		2.090	42.113		44.203
Nose Fairing	.999	.184		.734		1.917	50.191		52.108
Forward Skirt	1.060	.255	.051	.612		1.978	41.925		43.903
Base Support Skirt	2.345	1.326	.179	2.142		5.992	139.951		145.943
Heat Shield	.343	.029	.011	.043		.426	1.860		2.286
1.3.2 Ordnance System									
Ignition	.466		.041	.073		.580	.998		1.578
Separation	.282		.006	.025		.313	1.637		1.950
Range Safety (Destruct)	1.109	.088	.031	.169		1.397	12.267		13.664
1.3.3 Flight Safety Monitoring System	.262		.005	.018		.285	2.184		2.469
1.3.4 Flight Instrumentation	.865	.010	.063	.380		1.318	17.054		18.372
1.3.5 Electrical/Mechanical Hdw Set	.376	.047	.017	.122		.562	6.822		7.384
1.3.6 Installation Assembly & C/O	.993		.281	.553		1.827	7.722		9.549
1.3.7 Ground Tests			.082			.082			.082
Transportation			.061	.122		.183	8.976		9.159
3.3.1.4 Facilities									
3.3.1.5 System Support									
1.5.1 Support Equipment & Spares	.582			.115		.697	1.241	.665	2.603
1.5.2 Flight Test Support				.162		.162		1.969	2.131
1.5.3 Operations Support				.162		.162		4.568	4.730
TOTAL	10.905	2.194	.828	6.044		21.104	335.883	7.202	364.189

Stage Component Cost Estimate

Figure III-18

\$ in millions SRM with 1,250,000 lb propellant Parallel configuration Without TVC or TN	DDT&E ENGRG DESIGN & DEV (EDD)	DDT&E TOOLING (TOOL)	DDT&E GROUND TEST HDWR (GTH)	DDT&E FLIGHT TEST HDWR (FTH)	DDT&E OTHER (OTH)	DDT&E TOTAL (TOT)	PRODUCTION	OPERATIONS	TOTAL PROGRAM
3.3.2 SOLID ROCKET MOTORS									
3.3.2.1 Program Management						.628	.825		1.453
3.3.2.2 System Engineering						.854	.678		1.532
3.3.2.3 SRM's									
2.3.1 Structures									
Case	1.653	11.048	3.581	10.054		28.336	692.734		721.070
Insulation	1.465	3.018	.950	1.640		7.073	89.501		96.574
Nozzle (w/o Flex Seal)	1.515	3.527	2.351	4.025		11.418	287.744		299.162
Igniter	1.396	.234	.391	.164		2.185	8.446		10.631
Propellant	2.023		2.448	4.590		9.061	329.976		339.037
2.3.2 Motor Processing & Subassembly	2.176	12.987	3.405	6.507		25.075	119.306		144.381
2.3.3 Ground Tests		.594	.845			1.439			1.439
3.3.2.4 Facilities									129.314
3.3.2.5 Systems Support									
2.5.1 Support Equipment & Spares	.168					.168	6.944	4.936	12.048
2.5.2 Flight Test Support				.212		.212		2.609	2.821
2.5.3 Operations Support				.254		.254		6.052	6.306
3.3.2.6 Shipping				.070		.070	4.761		4.831
TOTAL	10.396	31.408	15.971	27.516		86.773	1,540.915	13.597	1,770.595

SRM Cost Estimate

Figure III-19

$ in millions SRM with 1,250,000 lb propellant Parallel configuration Without TVC or TN	DDT&E: ENGRG DESIGN & DEV (EDD)	DDT&E: TOOLING (TOOL)	DDT&E: GROUND TEST HDWR (GTH)	DDT&E: FLIGHT TEST HDWR (FTH)	DDT&E: OTHER (OTH)	DDT&E: TOTAL (TOT)	PRODUCTION	OPERATIONS	TOTAL PROGRAM
3.3.1 STAGE									
3.3.1.1 Program Management									
3.3.1.2 System Engineering						.491	.491		.982
3.3.1.3 Stage						.642	.451		1.093
1.3.1 Structures									
Attach Structures	1.294	.281		.673		2.248	46.324		48.572
Nose Fairing	.999	.184		.734		1.917	50.191		52.108
Forward Skirt	1.115	.281	.056	.673		2.125	46.118		48.243
Base Support Skirt	2.620	1.525	.206	2.463		6.814	160.944		167.758
Heat Shield	.343	.029	.011	.043		.426	1.860		2.286
1.3.2 Ordnance System									
Ignition	.466		.041	.073		.580	.998		1.578
Separation	.282		.006	.025		.313	1.637		1.950
Range Safety (Destruct)	1.189	.097	.034	.186		1.506	13.494		15.000
1.3.3 Flight Safety Monitoring System	.262		.005	.018		.285	2.184		2.469
1.3.4 Flight Instrumentation	.865	.010	.063	.380		1.318	17.054		18.372
1.3.5 Electrical/Mechanical Hdw Set	.376	.047	.017	.122		.562	6.822		7.384
1.3.6 Installation Assembly & C/O	1.043		.295	.581		1.919	8.018		9.937
1.3.7 Ground Tests			.082			.082			.082
Transportation			.070	.140		.210	10.322		10.532
3.3.1.4 Facilities									
3.3.1.5 System Support									
1.5.1 Support Equipment & Spares	.582			.115		.697	1.303	.798	2.798
1.5.2 Flight Test Support				.162		.162		1.969	2.131
1.5.3 Operations Support				.162		.162		4.568	4.730
TOTAL	11.436	2.454	.886	6.550		22.459	368.211	7.335	398.005

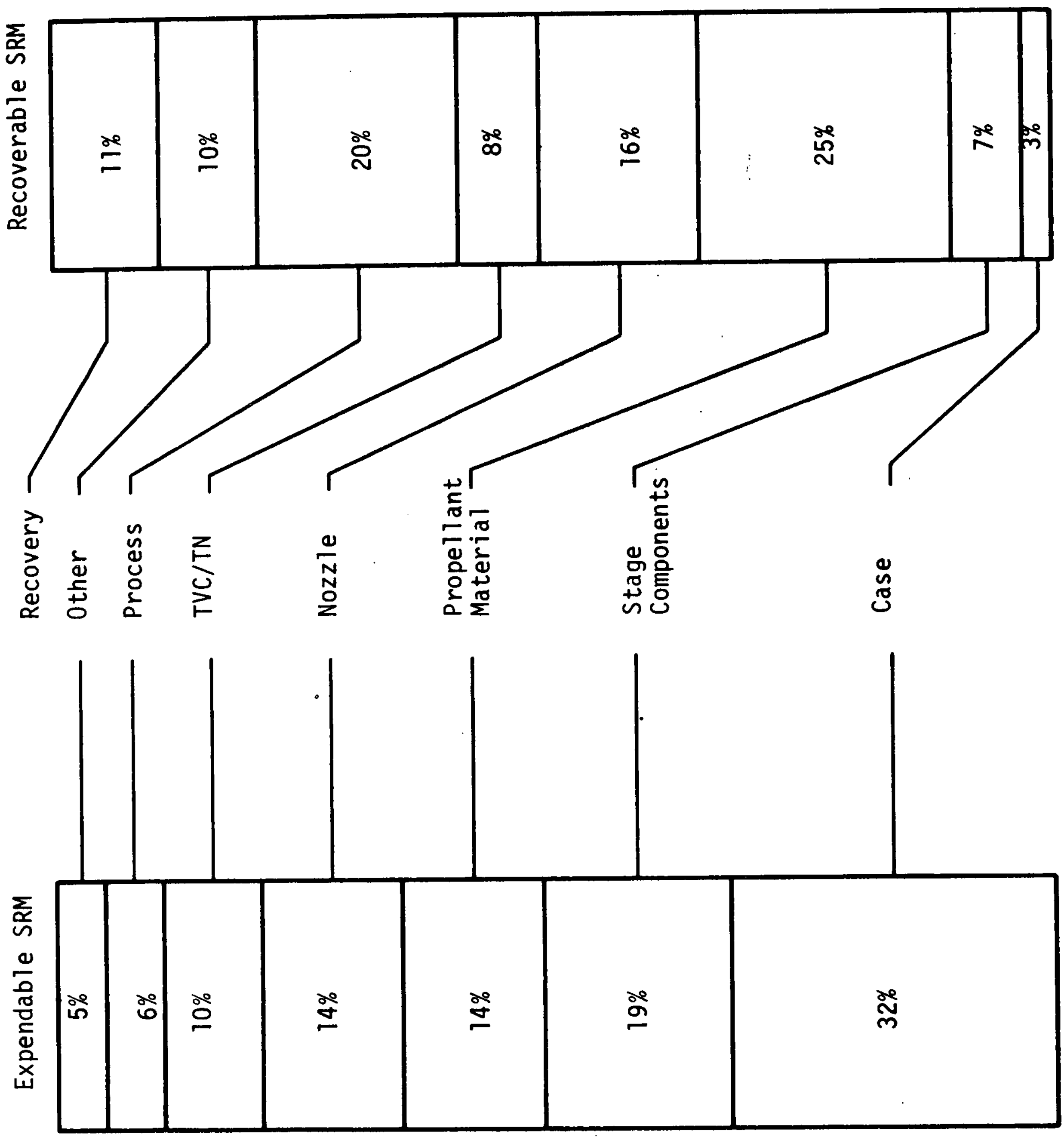
Stage Component Cost Estimate

Figure III-20

(Millions of 1970 Dollars)	Non-recurring	Facilities	Recurring	Total
Case (30 units)	(4.6)	(38.9)	(533.6)	(577.1)
Nozzle structural components (80% reuse)			(26.0)	(26.0)
Flexseal (50% reuse)			(30.5)	(30.5)
TVC system (50% reuse)			(15.7)	(15.7)
Motor refurbishment	1.1	7.2	31.0	39.3
Propellant (47,000lb additional/motor)			12.3	12.3
KSC operations	0.2		1.5	1.7
Stage structures and systems	(0.2)		(279.5)	(279.7)
Parachute system	86.8	17.7	72.0	176.5
Retro rockets	1.1		19.8	20.9
Location aids, floation, altitude sensor	12.0		17.6	29.6
Recovery operation, barge and tug	5.0		15.0	20.0
Recoverable booster cost delta	101.4	(14.0)	(716.1)	(628.7)
Expendable program costs (with TN and TVC)	111.2	112.4	1838.1	2061.7
Recoverable booster program costs	212.6	98.4	1122.0	1433.0
Percent change	+90.8	-10.7	-39.0	-30.5

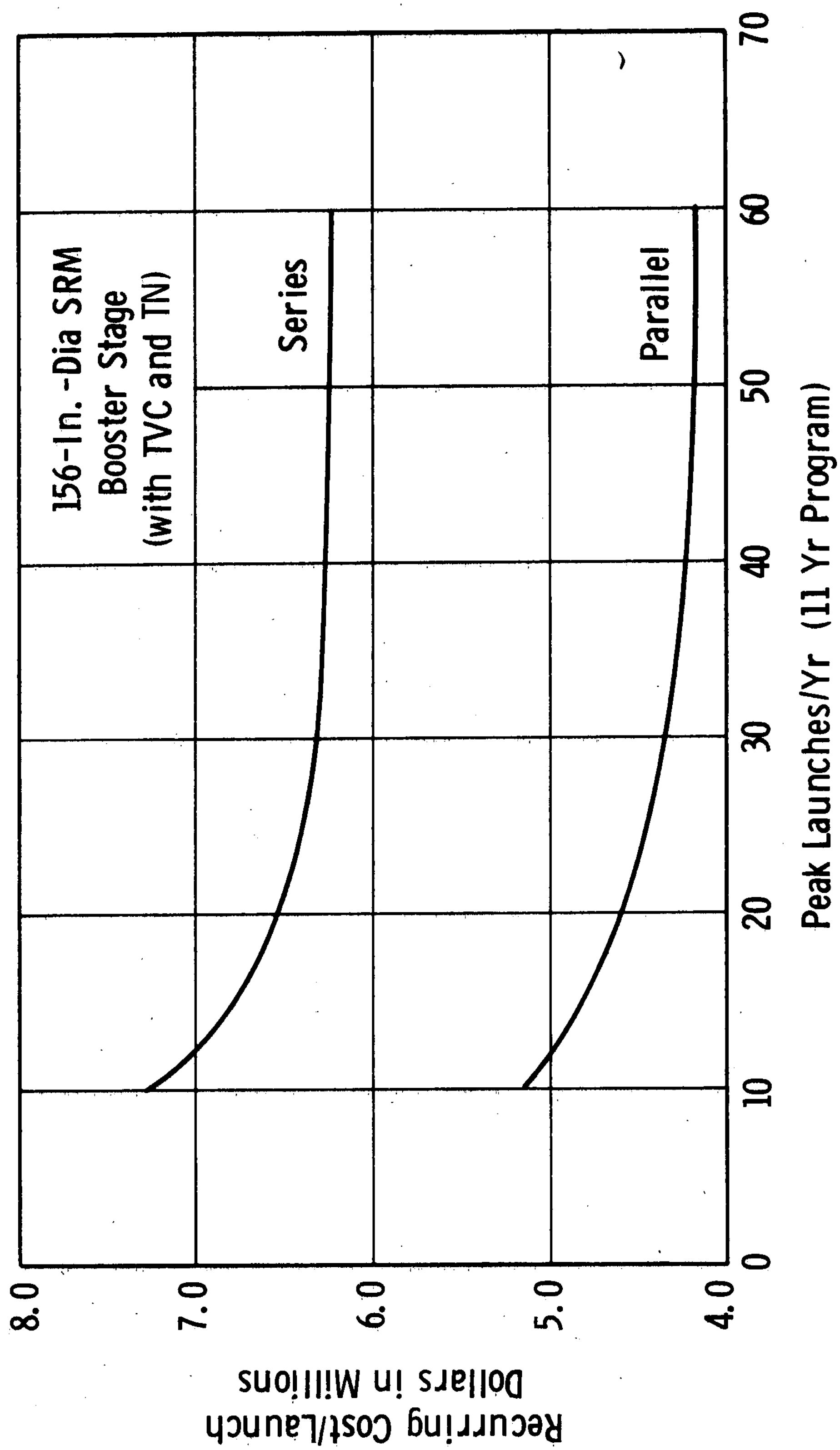
Cost Changes Resulting from Booster Recovery

Figure III-21



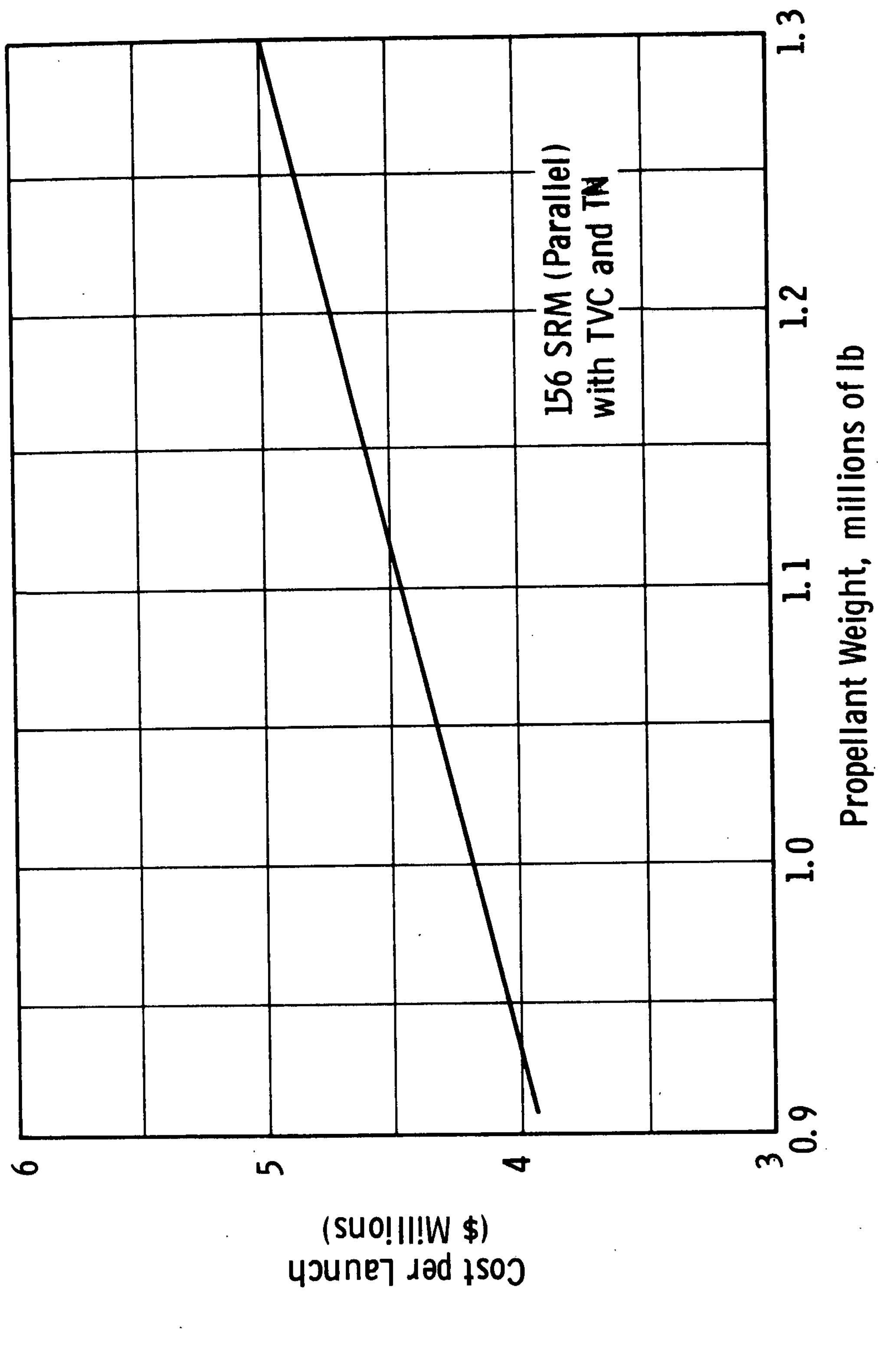
Relative Cost of SRM Components

Figure III-22



Launch Cost As a Function of Launch Rate

Figure III-23



Effect of Propellant Weight

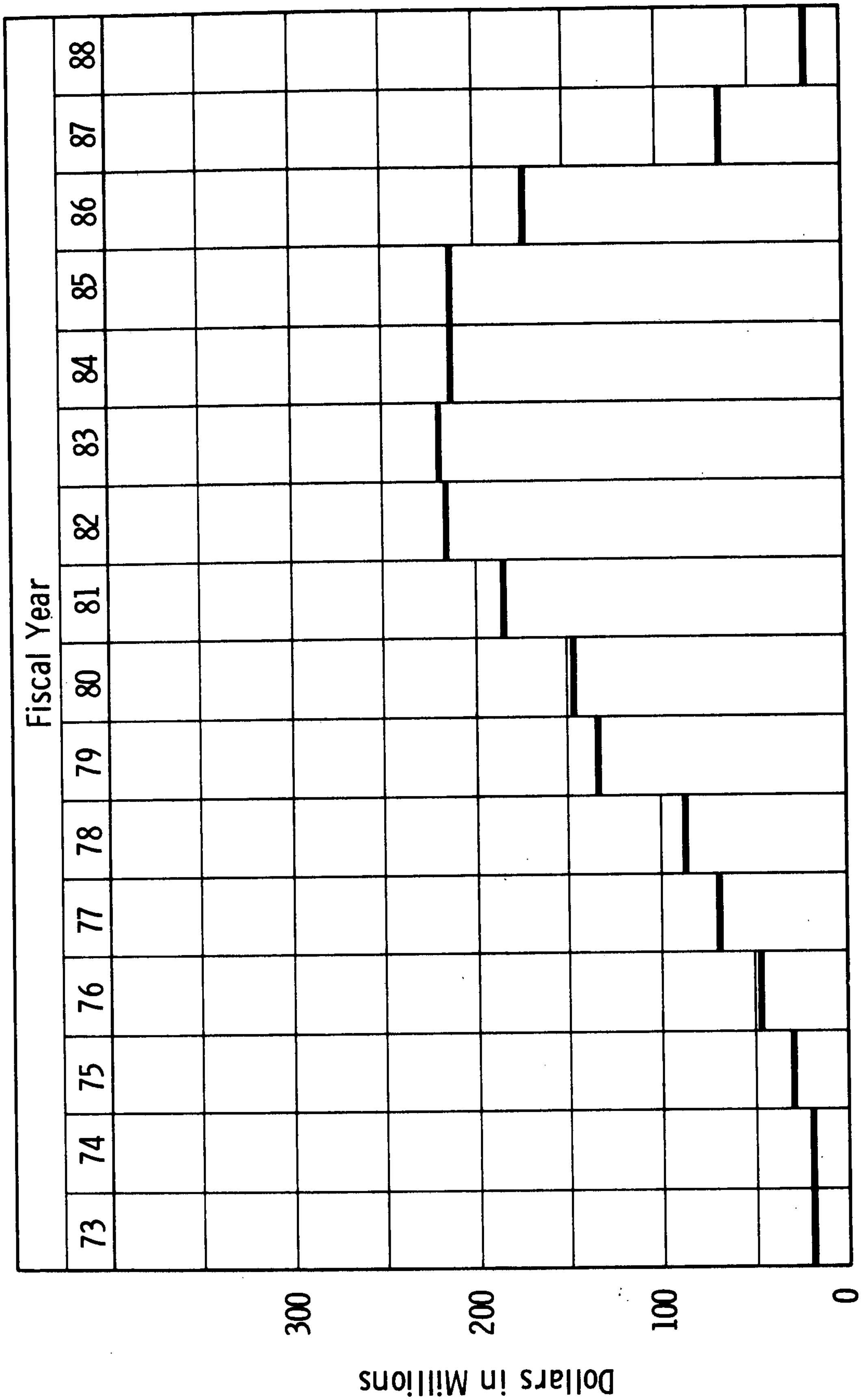
Figure III-24

Cost Background		Average Production
Description	Cost ($/lb)	156 SRM Cost ($/lb)
260 Case Fabrication (2 units)	11.15	9.00
120 Case Fabrication (*)	9.07	
260 Insulation (2 units)	8.95	6.00
120 Insulation (*)	9.61	
260 Nozzle (2 units)	34.50	25.30
260 Propellant Material (3 units)	0.306	0.289
260 Propellant Processing (3 units)	0.048	0.05
Titan IIIC Stage Components (First Production Unit)	29.00	18.00
Minuteman II Motor Processing Learning Curve Slope	90.7%	95%

(*Titan IIIC cost normalized to 890 units)

Related Cost Experience

Figure III-25



Time Phased Funding Requirements
(Baseline Program without TVC and TN)

Figure III-26

($ in millions)

COST ELEMENT / FISCAL YEAR	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	Total
NON-RECURRING TOTAL	9.9	13.0	15.1	21.6	7.0	5.3	1.0	.8	1.8	.9							76.4
DDT&E																	
DEVELOPMENT																	
DEVELOPMENT	5.4	7.5	2.4	3.0	2.3	2.3											22.9
STE/TOOLING	4.5	3.3	8.1	2.5	2.1	2.9	1.0	.8	1.8	.9							27.9
DELIVERABLE HARDWARE																	
DUMMY ENGINES		2.0															2.0
FLIGHT ENGINES			4.6	16.0	2.4												23.0
O&FS & SPARES		.2		.1	.2	.1											.6
RECURRING TOTAL				2.5	23.9	56.9	85.2	106.4	133.7	156.6	172.6	172.3	173.6	144.1	64.3	15.4	1,307.5
INVESTMENT																	
DELIVER NEW ENGINES				1.3	22.4	55.9	82.5	105.3	131.1	155.0	170.4	171.3	172.6	143.0	63.2	14.3	1,288.3
GROUND SUPPORT EQUIPMENT				1.2		.8	.8	.5	.6	.9							4.8
PARTS					1.5		1.4		1.4		1.4						5.7
OPERATIONS																	
FLIGHT SUPPORT						.1	.2	.2	.2	.2	.2	.3	.3	.3	.3	.3	2.6
OPERATIONS						.1	.3	.4	.4	.5	.6	.7	.7	.8	.8	.8	6.1
PARTS																	
FACILITIES	8.3	.1	7.0	15.1	21.8	5.7	18.8	6.2	6.8	16.1	6.3	.2					112.4
TOTAL PROGRAM	18.2	13.1	22.1	39.2	52.7	67.9	105.0	113.4	142.3	173.6	178.9	172.5	173.6	144.1	64.3	15.4	1,496.3

Time Phased Funding - SRM

Figure III-27

	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	Total
NON-RECURRING TOTAL	3.1	7.5	5.0	3.8	1.0	.7											21.1
DDT&E																	
DEVELOPMENT																	
DEVELOPMENT	3.1	3.9	2.8	1.0	.9	.6											12.3
STE		1.0		1.2													2.2
DELIVERABLE HARDWARE																	
DUMMY HARDWARE																	
FLIGHT HARDWARE		2.2	2.2	1.2													5.6
O&FS & SPARES		.4		.4	.1	.1											1.0
RECURRING TOTAL				5.4	15.3	21.3	26.9	32.4	37.3	42.8	42.7	43.0	42.7	27.9	3.0	2.4	343.1
INVESTMENT																	
DELIVER NEW HARDWARE				5.1	15.3	20.6	26.4	31.6	36.8	41.9	42.0	42.0	42.0	27.1	2.2	1.6	334.6
GROUND SUPPORT EQUIPMENT				.3		.2	.2										.7
PARTS						.3		.3		.3		.3					1.2
OPERATIONS																	
FLIGHT SUPPORT						.1	.1	.2	.2	.2	.2	.2	.2	.2	.2	.2	2.0
OPERATIONS						.1	.2	.3	.3	.4	.5	.5	.5	.6	.6	.6	4.6
PARTS																	
FACILITIES																	
TOTAL PROGRAM	3.1	7.5	5.0	9.2	16.3	22.0	26.9	32.4	37.3	42.8	42.7	43.0	42.7	27.9	3.0	2.4	364.2

Time Phased Funding - Stage Components

Figure III-28

IV. CONTRACT DATA LIST

The following data items have been provided in accordance with the Data Requirements Document for Contract NAS8-28428:

A. Presentation book for Study of Solid Rocket Motors for Space Shuttle Booster, dated 14 February 1972.

B. Presentation book for Study of Solid Rocket Motors for Space Shuttle Booster, dated 23 February 1972.

C. Mass properties report, Study of Solid Rocket Motors for a Space Shuttle Booster, Report 1917-MP-1, dated 15 March 1972.

D. Preliminary design data package, Study of Solid Rocket Motors for a Space Shuttle Booster, Report 1917-PD1, dated 15 March 1972.

E. Final report, Study of Solid Rocket Motors for a Space Shuttle Booster, Report 1917-FR1, dated 15 March 1972.

Report 1917-FR1 includes the following appendixes as separate volumes of the final report:

Appendix A - SRM Water Impact Loads

Appendix B - Typical SRM Components Recertification Test Procedures

Appendix C - Test Program Backup Data

Appendix D - Motor Processing Facilities

No restrictions are placed on the distribution and use of the above data, with the exception of Appendixes C and D to Report 1917-FR1. These two

IV. Contract Data List (cont)

appendixes contain detailed manufacturing and test planning information which, if disclosed outside NASA, could damage Aerojet's competitive position in any future shuttle booster procurement. It is therefore requested that Appendixes C and D be restricted to NASA internal use.

V. CONCLUSIONS AND RECOMMENDATIONS

The results of this study show that the SRM booster is a logical choice for the space shuttle. Use of an SRM booster means:

— Low Technical Risk

The necessary SRM technology has been proven. The relative simplicity of solid rockets results in demonstrated high reliability. Growth capability can readily be designed into the SRM booster if desired.

— Low and Credible Costs

All major cost elements of the SRM booster program are supported by directly applicable experience.

— No Critical System Problems

The environmental impact of SRM booster operation is modest, even at the maximum projected shuttle launch rates. SRM thrust neutralization if feasible and can be used as a part of a shuttle abort system.

VI. REFERENCES

VI. REFERENCES

(1) "Environmental Health Aspects - 120 in. Motor Firing," Aerojet-General Corporation Report, 1964.

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(3) Cesta, R. P., and McLouth, M. E., "Industrial Hygiene Study - Titan IIIC Launch," Final Report, Pan American World Airways, Inc., Aerospace Services Division, 15 December 1967.

(4) Engineering Memorandum L5-03-M1-5, "Preliminary Analysis of a SRM Recovery System and Definition of a Program Development Plan," Lockheed Missiles and Space Company, 31 January 1972.

(5) Report ML-TDR-64-53, "An Investigation of Low-Cycle Fatigue Failures Using Applied Fracture Mechanics," by C. F. Tiffany, et al., The Boeing Company, May 1964.

(6) "Fracture," by G. R. Irwin, Encyclopedia of Physics, Vol. VI, Springer, Berlin, 1958.

(7) Report AFML-TR-71-218, "Development of a Nondestructive Testing Technique to Determine Flaw Criticality", by C. E. Hartbower, Aerojet Solid Propulsion Company, January 1972.